Automatic Monitoring System in Underground Engineering Construction: Review and Prospect

1. Introduction

With the increasing complexity of underground engineering, the impact on the surrounding environment is more prominent [1–4], and the various technical problems follow. In the construction process, the increasing attention to ensure the safety of the surrounding environment and the requirement for automated industrial production has greatly increased the demand for the automatic monitoring system.

At present, the study of construction safety of underground engineering mainly adopts the traditional manual monitoring methods whose data collection process are cumbersome and time-consuming. With the development of industrial technology, more and more sensors are used in monitoring, including vibrating wire sensor [5], optical fiber sensor [6], and MEMS sensor [7]. Optical fiber sensors are the most widely used because of their high sustainability, high durability, long-term stability, spatial resolution, and high immunity to electromagnetic interference [8, 9]. Photogrammetric technology, which is often used in bridge monitoring, is gradually applied to the underground engineering monitoring system [10]. In data transmission, traditional manual monitoring methods cannot provide high spatial and temporal resolution. Most of the research focuses on the wireless sensor network technology (WSN), and it is widely used in coal mining monitoring. Bo et al. [11] proposed a safety monitoring system for an underground coal mine based on the wireless sensor network. Li and Liu [12] put forward a wireless sensor network system for early detection of underground coal mine collapse and roof fall accident. Based on Bayesian decision-making, Chen et al. [13] discussed the correcting method of WSN nodes in monitoring and identifying hidden dangers of mine tunnel. In recent years, the research on monitoring data analysis and processing has aroused great concern. Adoko et al. [14] established a model based on Regression Spline (MARS) and Artificial Neural Network (ANN) to predict the convergence of tunnel diameter in high-speed railway and achieved good...
results. Xiao et al. [15] put forward an effective method to estimate the optimal construction time of secondary connection of a circular tunnel based on the grey prediction model GM(1,1). At the same time, linear, nonlinear models, wavelet analysis, and chaotic time series are also well applied in underground engineering monitoring data processing, but there is still no better model to meet the needs of underground engineering monitoring, and the prediction accuracy needs to be further improved.

With the rapid development of big data and cloud computing technology, the application of the Internet of Things (IoT) is becoming more and more popular. Ding and Zhao [16] carried out a critical review on the application of Internet of Things in underground mining of coal mines, pointing out the lack of low-power intelligent sensors, environment energy capture technology, data protection safety network, public service platform, and underground IoT technical standard for further application in underground coal mines. Based on the IoT, Zhang et al. [17] designed a three-dimensional visualization monitoring system and safety control platform for an underground coal mine.

This paper summarizes the current research status of the underground engineering monitoring system from three aspects of data acquisition, data transmission, and data processing and emphatically introduces several typical monitoring systems at present. Based on the current intelligent technology and the challenges faced by future monitoring, this paper proposes specific and implementable technical routes which can provide direction and reference for future research.

2. Layout of Monitoring Points and Safety Control Standards

In order to ensure the safety of construction period, some monitoring standards have been formed, including tunnel engineering [18], foundation pit engineering [19, 20], and urban rail transit underground engineering monitoring [21]. The layout of monitoring points during the construction period can usually be arranged according to relevant standards. The three-dimensional numerical simulation can be used to simulate and calculate the distribution of displacement, stress, and plastic zone of the structure and surrounding environment in underground engineering construction; the monitoring points are located at the position where the control parameters (displacement, stress, or plastic zone) are larger. At present, the commonly used monitoring safety control index are horizontal displacement, vertical displacement, surface vertical displacement, and so on, as shown in Table 1. The technical standards for monitoring construction foundation pit engineering [20], Shanghai foundation pit engineering technical standards [21], and Shenzhen urban rail transit underground engineering monitoring standards [22] are presented.

Qian and Rong [23] pointed out that the standards related the technical control index for underground engineering are not comprehensive enough. For example, according to the existing standards, the control standards for ground subsidence in underground engineering construction are not more than 30 mm which is considered loose in some projects with higher risk levels; but for some projects, the control values are unnecessary. In addition, the safety control index database system adapted to different geotechnical, hydrogeological, and environmental conditions in different cities and different construction methods has become a top priority. Therefore, the research on the safety control index of underground engineering monitoring will be the key research direction [24].

3. Framework of the Monitoring System

As shown in Figure 1, the typical underground engineering monitoring system is composed of four parts: data acquisition, data transmission, data analysis and processing, and security state early warning. The data acquisition terminal mainly uses sensors and cameras. Data transmission adopts wired and wireless modes; data analysis and processing adopt a variety of intelligent algorithms and early warning system forecasts security status based on the processing results.

3.1. Data Acquisition

3.1.1. Traditional Data Acquisition. Underground engineering monitoring content generally includes the stress, strain, displacement, and other parameters affecting the stability of rock mass. According to “Technical Standards for Highway Tunnel Construction” [25], the necessary items include observation inside and outside the tunnel, settlement of vault, surrounding displacement, and ground settlement. The observation inside and outside the tunnel is mainly recorded by manual field, and the surrounding displacement of rock mass after excavation is monitored by using a convergence meter [26]; the surface subsidence and vault subsidence are monitored mainly by using a leveling instrument and steel ruler or total station instrument. There are also some selected items, for example, the relative displacement between anchoring points of different depths in rock mass is monitored by using an extensometer [27, 28]; tunnel anchor axial force is monitored by using a steel bar gauge [29]. The main monitoring methods and instruments are shown in Figure 2. Traditional monitoring methods acquire data manually, which makes the person exposed to dangerous environment for a long time. Also, the method is time-consuming and will affect the excavation schedule. Therefore, the automation of data acquisition has attracted more and more attention.

3.1.2. Sensor Acquisition. Due to the limitations of traditional monitoring methods, it has become a hotspot to collect data automatically with various sensors in recent years, among which vibrating wire sensors, optical fiber sensors, and MEMS sensors are used more frequently.

(1) Vibrating String Sensor. The vibrating string sensor is a kind of sensor, which expresses the magnitude of tension by the change of natural vibration frequency of a metal string sensor and converts it into an electrical signal [30, 31]. The
principle is shown in Figure 3. Vibrating string sensors are widely used in long-term monitoring of civil buildings, reservoirs, dams, tunnels, and bridges in harsh environments due to their strong anti-interference ability and resistance to temperature. Based on the principle of the vibrating string sensor [5], a steel frame was designed to estimate the prestress of concrete effectively and reduce the monitoring cost greatly. In order to evaluate the operation performance of the Wuhan Yangtze River underwater tunnel, Yang et al. [32] used the vibrating-string surface strain gauge and joint measurement to monitor tunnel deformation; the instrument has been installed for more than three years, and 83.3% of the sensors work well. Moyo [33] found that the vibrating string strain gauges installed on bridges could still operate after eight years in Singapore and Malaysia. All these

| Monitoring projects | Horizontal displacement | Vertical displacement | Deep horizontal displacement | Soil pressure | Wall internal force | Supporting force |
|--------------------|------------------------|----------------------|-----------------------------|--------------|--------------------|-----------------|
| [20]               | 25–30                  | 10–20                | 30–35                       | (60%–70%) f 1| (60%–70%) f 2 80% f 3-70% f 2 |
| [21]               | 15–25                  | 15–25                | 30–50                       |              |                    |                 |
| [22]               | 30                     | 40                   | —                           |              |                    |                 |

$f$: design limit value; $f_1$: load design value; $f_2$: bearing capacity design value; $f_3$: prestress design value.

**Figure 1**: Overall architecture of the monitoring system.

**Figure 2**: Traditional monitoring data acquisition.

**Figure 3**: Vibrating-string sensor structure.
studies clearly show the long life performance of the vibrating-string strain gauge.

(2) Optical Fiber Sensors. Hill et al. [34] first proposed Fiber Bragg Grating (FBG) in 1978. It was developed for telecommunication technology originally. But, since the 1990s, optical fiber technology has developed rapidly in the sensor field with the advantages of multiplexing, anti-electromagnetic interference, high precision, and good reliability. Its principle is shown in Figure 4. When the stress, strain, or other physical quantities of the grating environment change, the grating period $\Lambda$ or the refractive index $n$ will change, so that the reflected light wavelength $\lambda$ will change. By measuring the change in the wavelength, the change in the physical quantities to be measured can be obtained. Sato et al. [6] used FBG sensing technology to measure ground strain, compared with the traditional measurement results, and verified that FBG has better accuracy. Wu et al. [35] developed a new type of optical fiber displacement sensor based on the bending single-mode-multi-mode-single-mode (SMS), which has a larger displacement monitoring range.

In recent years, Brillouin Optical Time Domain Analysis (BOTDA) based on FBG sensors has attracted the attention of many researchers. As a new type of fully distributed strain monitoring sensor technology, the main advantage of BOTDA sensor technology is that it does not reduce the spatial resolution in long-distance monitoring. In order to verify the practicability of BOTDR, Mohamad et al. [36] used this sensing technology to monitor the strain distribution along the tunnel based on Singapore’s New Ring Line Metro Project and has good consistency with the traditional monitoring results. Using the Brillouin Optical Time Domain Reflectometry (BOTDR) technology, Cheung et al. [37] established a strain monitoring system for monitoring the displacement of concrete tunnel lining joints in London underground tunnels.

(3) MEMS Sensors. The microsensor is the most successful and practical microelectromechanical device at present. It has the characteristics of small size, light weight, and good performance. In addition, there are micro-temperature sensors, magnetic field sensors, gas sensors, and so on. The area of these microsensors is mostly less than 1 mm².

Microelectromechanical system (MEMS) sensors have been widely used in airbag deployment in the automotive industry. They are also gradually used in geotechnical engineering monitoring. Danisch et al. [38] fused the MEMS sensor with the automatic geodetic monitoring system to provide the necessary information for determining the three-dimensional displacement, strain field, and rigid body motion of deformable objects. Densenbrock [7] used the shape acceleration array SAA based on the MEMS sensor (SAA is a new geotechnical instrument developed by Rensselaer Institute and Measureand Inc.) to monitor landslides. SAA is an array consisting of hundreds of MEMS accelerometers, which has achieved better results than traditional methods. Rollins et al. [39] used the shape accelerometer array (SAA) to determine the horizontal displacement and depth profile during the lateral pile load test.

In view of the abovementioned three sensors commonly used in underground engineering monitoring, their advantages and disadvantages are compared as shown in Table 2.

As can be seen from the table, the three types of sensors have their own advantages and disadvantages, among which the advantages of optical fiber sensors are prominent, and they have developed rapidly in the recent years. From 2012 to 2017, the average annual increase of consumption value of global optical fiber sensors has reached 20.3%. The United States occupies the vast majority of the global market share of optical fiber sensors. At the same time, it is expected that the Asia-Pacific region will become the fastest growing market with an annual compound growth rate of 12.7% between 2015 and 2020.

Although the optical fiber sensor technology has been applied in practical monitoring, there are still some problems, namely, the output signal of the optical fiber sensor will be affected by the fluctuation of the light source, the change of the transmission loss of the optical fiber, the aging of the detector, and other factors, which will reduce the accuracy of the measurement. In view of the special environment of underground engineering, the performances of sensors need to be further improved.

3.1.3. Photogrammetry. In order to better realize the automation of monitoring, photogrammetry technology [43–46] has gradually attracted more and more attention. The timely triggering and management of monitoring results can be strengthened through immediate visual inspection of photogrammetry, which has been widely used in bridge monitoring [47, 48]. However, it is seldom used in other infrastructure projects. Take et al. [10] proposed a real-time monitoring technology of construction settlement based on photogrammetry, which combines remote digital photography technology, automatic file transmission technology, and image processing technology of particle image velocimetry (PIV). The technology is applied in monitoring the settlement of retaining wall caused by tunnel excavation. White et al. [49, 50] explained how to apply some effective algorithms to photogrammetric systems to track and monitor objects. For long-term environmental change monitoring, Alhaddad [51] developed software named CSATTAR (Satellite Image Tracking) based on the existing photogrammetric monitoring technology. Although considerable progress has been made in the field of tunnel monitoring, due to various challenges in this field, the application of photogrammetry has not been fully developed.

3.2. Data Transmission. Traditional manual monitoring methods cannot provide high spatial and temporal resolution. In order to alleviate this problem, advanced countries have adopted online monitoring systems. However, these systems adopt wired communication, which has some shortcomings such as damageable communication cable, high failure rate, and inconvenient system maintenance. In the recent years, more and more scholars have used wireless communication technology to transmit data collected by
sensors, which is called wireless sensor network technology (WSN) [52–54]. This technology has outstanding advantages such as easy configuration, flexible topology change, strong fault tolerance, and mobility.

3.2.1. Transmission Principle. As shown in Figure 5, a typical WSN is usually composed of various monitoring sensor nodes, cluster head nodes, and base stations. WSN nodes with an information acquisition function are scattered in the designated monitoring area. The collected data are sent to cluster head nodes in the form of wireless communication. The cluster head is only used to route information to receivers to reduce power consumption. Then, it is transmitted to the base station by the multihop relay transmission mode. Base station is a nonmobile node, which can receive and transmit data throughout the system and finally reach the control center through the Internet or LAN [55, 56].

3.2.2. Comparative Analysis of Transmission Modes. At present, Bluetooth, Wi-Fi, Ultra Wideband Technology (UWB), and ZigBee are widely used in underground engineering monitoring. It has different parameters in frequency band, transmission power, transmission power, channel number, and so on, as shown in Table 3 [57–60].

It can be seen from the table that Wi-Fi is suitable for long-distance transmission and the other three communication technologies are suitable for short-distance. In terms of data transmission efficiency, UWB technology has the highest transmission efficiency, while ZigBee is suitable for low data transmission efficiency requirements; in terms of power consumption, Bluetooth and ZigBee have the lowest power consumption for the output of short-distance transmission signals; in the signal frequency band, Blue- tooth, ZigBee, and Wi-Fi all use spread spectrum technology in the free 2.4 GHz band; and the maximum number of nodes that ZigBee can reach is 65000.

Underground engineering monitoring needs a large number of sensor nodes to collect and transmit data in the detection area, and the underground environment is more complex, which also puts forward high requirements for wireless communication technology. By comparing the abovementioned four communication technologies, we can see that the communication technology based on ZigBee is a good choice for underground engineering because of its advantages of low cost, low power consumption, more
nodes, and long transmission distance. Also, the ZigBee technology adopts spread spectrum technology, which effectively improves the antijamming ability and maintains stability [61, 62].

3.2.3. Transmission Problems. The high-frequency data acquisition of automatic monitoring causes a large amount of monitoring data, and the wireless transmission is susceptible to interference. Therefore, data compression [63–66] and data reliability become the main problems in data transmission.

Compression ratio, data recovery error, energy consumption, transmission delay, and complexity are considered to evaluate the performance of data compression. Based on the traditional single-node compression technology, distributed data compression, such as distributed K-L transform, distributed wavelet transform, and distributed compressed sensing, is carried out by utilizing the temporal correlation within sensor nodes and the spatial correlation between sensor nodes [67]. The research of technology is of great significance to improve the performance of data compression in deformation monitoring of wireless sensor networks [68].

Current research mainly focuses on two aspects to solve the problem of data reliability: the design of reliable transmission protocol and the recovery of lost data. Nagayama and Spencer [69] designed a reliable communication protocol in wireless sensor network monitoring. Data interpolation is the common recovery technology. Bao et al. [70] studied the technology of data recovery using compressed sensing. Data recovery reduces data retransmit rate and saves network resources.

3.3. Data Processing and Analysis. For the safety of underground engineering, forecasting is the ultimate goal and monitoring is only the means of analysis. There are many factors causing deformation in underground engineering. It is of great significance to correctly analyze and explain the various factors affecting deformation. Nowadays, artificial intelligence is a hot research field and the direction of future social development. Machine learning, as an important research field in artificial intelligence, has been paid more and more attention to. How to use the construction status and monitoring data to predict underground engineering construction is still a big problem. Monitoring data is a small sample; exploring learning rules in limited samples is a difficult problem.

3.3.1. Common Data Processing Model. The regression analysis method, time series method, Kalman filter method, grey model method, wavelet analysis method, and neural network algorithm are commonly used in the processing and prediction of underground engineering deformation monitoring data. Kim et al. [71] used the neural network model to predict ground subsidence caused by tunnel excavation. Lai et al. [72] applied the neural network to prediction of soil deformation in tunnels. Relying on this project of Karaji Metro Line 2, Moghaddasi and Noorian-Bidgoli [73] proposed a prediction model, which combines independent

| Parameter                   | Bluetooth | UWB         | Wi-Fi       | ZigBee       |
|-----------------------------|-----------|-------------|-------------|--------------|
| Frequency band              | 2.4 GHz   | 3.1–10.6 GHz| 2.4 GHz     | 2.4 GHz      |
| Maximum data transmission rate | 1 Mb/s   | 110 Mb/s    | 54 Mb/s     | 250 kb/s     |
| Transmission distance       | 10 m      | 10 m        | 100 m       | 10–100 m     |
| Power                       | 0–10 dBm  | −41.3 dBm/MHz| 15~20 dBm  | (−25)~0 dBm  |
| Network extension           | Scattering network | Point-to-point | ESS        | Tree/reticulate |
| Maximum number of nodes     | 8         | 8           | 2007        | >65000       |
component analysis (ICA) with artificial neural network (ANN).

In order to overcome the shortcomings of the traditional neural network algorithm, a single hidden layer feed forward neural network algorithm (ELM) was proposed. The algorithm has fast learning speed and good generalization performance, so it has better application. Liu et al. [74] first proposed an improved extreme learning machine (ELM) algorithm based on convergent data to predict transverse shear stress. The accuracy of the improved ELM algorithm was verified by practical engineering cases. Lian et al. [75] predicted landslide displacement by using the ELM model of modified empirical mode decomposition. The principles and characteristics of deformation data processing and prediction methods are shown in Table 4.

3.3.2. Problems in Data Processing

(1) Less samples

The prediction model has too few training samples, which makes it difficult to guarantee the reliability of the prediction model.

(2) Adaptability

Lack of data mining of internal characteristics and lack of discussion on the applicability of the prediction model.

(3) There are many factors

There are many factors that affect the construction safety of underground engineering. However, most of the prediction models only analyze the data for a single measurement point and do not consider the spatial characteristics of the data.

4. New Technique of an Underground Engineering Monitoring System

4.1. Wireless Multimedia Sensor Network Monitoring System

In the recent years, with the rapid development of MEMS, wireless communication, embedded system, distributed processing, and wireless sensor technology, the technology of wireless sensor network (WSN) has been greatly improved. Considering the constraints of underground engineering environment, WSN has been widely used and developed in underground engineering monitoring due to its advantages of no wired connection and the efficient data transmission mode by sensor nodes.

Muduli et al. [98] proposed an underground fire monitoring system of coal mine, which is based on the wireless sensor network technology. The system used the fuzzy logic method to improve the reliability of the decision-making process and reduce the hidden danger of coal mine fire. Othman and Shazali [99] summarized the application of wireless sensor networks in environmental monitoring and verified the effectiveness of wireless sensor networks. Mishra et al. [100] designed a wireless real-time monitoring platform for geotechnical sensors based on vibration string, which realizes continuous, real-time, and remote monitoring of stratum dynamics. The results are in good agreement with laboratory tests and field demonstrations. Taking the tunnel under construction in Shaanxi Province as the engineering background, the vibration response of the tunnel under blasting was monitored by using the wireless sensor network system [101], as shown in Figure 6. For the safety of workers, Yun et al. [102] developed a set of working face safety monitoring systems to judge the risk of working face collapse during tunnel construction.

Han et al. [103] proposed a wireless multimedia sensor network technology for underground coal mine based on traditional wireless sensor network and applied it to underground coal mine monitoring. The framework fills the gap in the design of an underground engineering wireless sensor network which lacks efficient and comprehensive structure.

The abovementioned research shows that the existence of the wireless sensor network monitoring system can achieve better target parameters for underground engineering monitoring, which has many types and large number of sensors, wide monitoring area, scattered layout of measuring points, low frequency data acquisition, and high networking requirements, but it has not been widely used. In addition, in order to improve the effectiveness of the underground engineering monitoring system, the concept of intelligent monitoring combined with advanced technologies such as Internet of Things attracted more attention.

4.2. Deformation Monitoring System of Underground Engineering Based on Internet of Things

The Internet of Things (IOT) is regarded as a new generation of ICT industry. It combines sensors, RFID tags, actuators, and mobile phones to achieve integrated sensing and intelligent processing. The development of Internet of Things technology provides great benefits to establish a fast, high precision, real-time, and high reliability automatic monitoring system for underground engineering.

Zhou and Ding [106] proposed a security barrier early warning system based on Internet of Things (IOT) to achieve a safe underground construction. The implementation of the construction site of the Yangtze River crossing subway tunnel shows that the safety performance of the project has been improved and the occurrence of dangerous energy accidents on-site can be prevented. Jo and Khan [107] introduced a reliable, efficient, and cost-effective Internet of Things air quality monitoring system for monitoring a complex, dynamic, and harsh underground coal mine environment and added evaluation and pollutant prediction functions, which achieved good results. Wu et al. [108] have established a dynamic information platform for underground coal mine based on the Internet of Things technology. The platform consists of six functional layers, including a support layer, perception layer, transmission layer, service layer, data extraction layer, and application layer. It provides a three-dimensional virtual mine system, safety diagnosis system, safety detection system, and emergency rescue system for coal mines.
### Table 4: Deformation data processing and prediction method analysis.

| Model               | Principle                                                                                           | Advantage                                                                 | Disadvantage                                                                 |
|---------------------|------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Regression analysis | According to the correlation between the observed external causes and the measured deformation, the mathematical model of load-deformation relationship is established | Static data processing; empirical model simulation; and simple calculation | A lot of data is needed                                                       |
| Kalman filter       | Find the law between input and output data of the system, and evaluate the state of the system based on the linear state equation | Data dynamic processing; only focuses on input and output, no need for historical data; and noise is white noise | Poor transient data processing                                               |
| Grey model          | Based on partial displacement information, the long-term deformation of underground structures is analyzed | Prediction can be based on incomplete data; a disordered sequence can be transformed into an ordered sequence | It is difficult to accurately predict the data with large fluctuation, which is suitable for the prediction that meets certain characteristics |
| Wavelet analysis    | According to the time-space frequency localization, the displacement variation law is analyzed, and the specific parameters of the input-output relationship function of the system are refined step by step | Localization analysis; adaptive analysis data; and good denoising ability | The selection of wavelet bases is difficult                                   |
| Wavelet analysis    | A new information processing system imitating and extending human functions                         | Parallel collaborative processing of data; efficient identification of nonlinear transforms; reduction of irrelevant factors, consideration of a large number of quantitative and qualitative factors, and assurance of accuracy | Overtuning, local minimum, stop criteria, and long calculating time          |

*Figure 6: Wireless sensor network system [101].*
Jo et al. [109, 110] have studied a highly accurate FBG monitoring system and developed a comprehensive mine structural safety system by only output data-driven methods on the Internet of Things (IOT) platform. The system has been successfully implemented in Hassan Kishor Coal Mine in Salt Field, Pakistan. Ding et al. [111] proposed a real-time early warning system for underground construction safety based on Internet of Things. The system can realize real-time perception, real-time transmission, and real-time early warning and can timely inform every underground construction site works. It has been successfully applied to the construction site of the Bed Metro Tunnel crossing Yangtze River. Most importantly, the system pays more attention to the integration of security monitoring and real-time early warning compared with the traditional methods. Therefore, more potential accidents can be identified and prevented before they occur, as shown in Figure 7.

The current prominent problems are “more conceptual solutions, less practical systems; more experimental systems, less scale applications,” which is not enough to form a representative system solution.

5. Development Trend Prospect of Underground Engineering Monitoring

Underground engineering will develop towards a super-large-scale, superdeep, integrated, interconnected, and more complex construction environment [112–115], which put forward higher requirements for its monitoring and control [116, 117]. In order to meet the needs of safety construction of underground engineering, the development trend of the existing automatic monitoring system for safety status of underground engineering can be summarized as follows.

5.1. High-Precision Real-Time Acquisition and Safe and Reliable Transmission of Monitoring Data.

BOTDA monitoring technology is the hottest research field at present, but the accuracy of the sensing technology cannot meet the requirements for some special environments. It is necessary to develop high-precision data acquisition equipment and reserve relevant data and communication interfaces to form a unification.

In the construction environment of an urban underground large space, the multipath propagation of wireless signals is very serious (even causes communication blind area) because of its semiclosed or fully closed structure. Therefore, the transmission of data or information will face three challenges: power supply of communication equipment, transmission mode, and layout of communication nodes. For large space communication between inside and outside: large space internal monitoring data are linked to external public network (4G/5G) or management private network through a gateway. For large space internal communication: a leak communication mode is adopted, and a uniform and continuous electromagnetic field around the

---

**Figure 7: Real-time early warning system for underground construction safety based on Internet of Things [111].**
coaxial cable is used as a transmission medium to realize the communication between monitoring point and data gathering center; in a wireless local area network (WLAN), the wireless transmission node gathers and forwards data by laying many wireless signal hotspots in an underground large space. These nodes and access points constitute the construction monitoring network of an urban underground large space; the node antenna can adopt a directional mode or antenna array mode.

5.2. Multisource Data Fusion, Security State Prediction, and Hierarchical Early Warning

5.2.1. Preprocessing and Fusion of Multisource Massive Monitoring Data

Data preprocessing: Fourier transform, multiscale wavelet transform, and singular spectrum analysis are used to reduce the noise of various monitoring data with weak signal change and strong interference. In view of the possibility of abnormality and loss of complex environment data, historical smoothing, proximity algorithm, machine learning, and other methods are used to elimination of data and completion of missing data. The preprocessing technology can improve the validity and reliability of the data which is important for the evaluation and evaluation model of construction safety state.

Data fusion: according to the space-temporal correlation characteristics of monitoring data, singular value decomposition and compressed sensing are used to fuse information at the data level, feature level, and decision level to reduce data redundancy. Based on the traditional random fusion methods such as the weighted average method, Kalman filter method, and multi-Bayesian estimation method, multivariate data fusion is the next development trend combined with artificial intelligence algorithms such as fuzzy logic theory, neural network, rough set theory, and learning technology. It lays a foundation for improving the accuracy and robustness of the evaluation model of construction safety state.

5.2.2. Prediction of Safety State. On the basis of data fusion, through deep mining of historical construction monitoring...
data, the intrinsic logic and law of the data are found. In addition to the traditional linear prediction model, artificial intelligence algorithms based on the stochastic forest, deep belief network, cyclic neural network, and long-short sequence model should be studied for single monitoring index data [118–120]. The data processing and prediction process is shown in Figure 8.

5.2.3. Hierarchical Early Warning. Through statistical analysis of a large number of engineering cases, emergency plans of different levels are determined according to different environments and different work methods. The emergency plans include a specific emergency treatment process, information feedback and processing mechanism, personnel dispatching scheme, risk control scheme, and related management rules and regulations [121–124]. An information tracking system for postemergency disposal is established and an emergency plan system associated with an environment and construction method is formed, as shown in Figure 9.

5.3. Cloud Platform for Visual Intelligent Monitoring and Early Warning. The real-time transmission data and engineering information model are calibrated in the space and time dimension by using a computer, and the trend of data change and real-time monitoring video are presented in the information model. Monitoring data can be knowable and visualized by using graphics, image processing, computer vision, and a user interface. Figure 10 shows the framework of an automated monitoring system based on intelligent algorithms. It includes a data acquisition layer, data transmission layer, data analysis layer, monitoring cloud platform, and display terminal. It can realize large-scale underground engineering safety visualization monitoring during construction, rapid analysis and command control, and early warning and timely feedback control of structural and environmental imperfections.

6. Conclusions

(1) In view of the necessity and urgency of underground engineering monitoring, this paper introduces the underground engineering monitoring system from three aspects of data acquisition, data transmission, and data processing. In data acquisition, optical fiber sensors have obvious advantages and rapid development; in data transmission, ZigBee-based wireless transmission has become the mainstream trend; in data processing and analysis, various models emerge endlessly, and each has its own advantages and disadvantages. The neural network model has developed rapidly in the recent years; the combination model of the neural network model and other models shows better prediction accuracy.

(2) The new methods and new technologies of the underground engineering monitoring system are shown in this paper, including the wireless multimedia sensor network monitoring system and deformation monitoring system of underground engineering based on IoT. Although these new technologies have good monitoring effect, they have not been widely used.

(3) Based on our previous research results, this paper expounds the development trend of underground
engineering monitoring technology and puts forward specific and implementable technical route. It mainly includes high-precision real-time acquisition and safe and reliable transmission of monitoring data, multisource data fusion, security state prediction and hierarchical early warning, and cloud platform for visual intelligent monitoring and early warning. It can provide direction and reference for future research.

(4) The heterogeneity and diversity of materials and the complexity of construction environment will pose further challenges to the design and application of monitoring systems in the future because of the development of underground engineering structures towards super-large-scale, superdeep, comprehensive, and interconnection.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

Acknowledgments
The authors gratefully acknowledge the financial support from the National Key R&D Program of China (no. 2018YFC0808706) and the Project on Social Development of Shaanxi Provincial Science (no. 2018SF-378).

References

[1] L. Q. Cao, D. L. Zhang, and Q. Fang, "Movements of ground and existing structures induced by slurry pressure-balance tunnel boring machine (SPB TBM) tunnelling in clay," Tunnelling and Underground Space Technology, vol. 97, Article ID 103278, 2020.

[2] E. L. Ma, L. X. Wang, J. X. Lai et al., "Cutting-edge sensing technologies for urban underground construction," Measurement, vol. 160, 2020.

[3] T. Liu, Y. J. Zhong, Z. H. Feng, W. Xu, F. Song, and C. Li, "New construction technology of a shallow tunnel in cobble-cobble mixed grounds," Advances in Civil Engineering, vol. 2020, Article ID 5686042, 20 pages, 2020.

[4] Z. Song, G. Shi, B. Zhao, K. Zhao, and J. Wang, "Study of the stability of tunnel construction based on double-heading advance construction method," Advances in Mechanical Engineering, vol. 12, no. 1, p. 17, 2020.

[5] S. Biswal and A. Ramaswamy, "Measurement of existing prestressing force in concrete structures through an embedded vibrating beam gauge," Measurement, vol. 83, pp. 10–19, 2016.

[6] T. Sato, R. Honda, and S. Shibata, "Ground strain measuring system using optical fiber sensors," in Proceedings of the Smart Structures and Materials 1999: Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials, vol. 3670, pp. 470–479, Newport Beach, CA, USA, March 1999.

[7] D. D. Dahlenbrock, "Automated landslide instrumentation programs on US route 2 in Crookston, MN," in Proceedings of the Annual Conference of the Minnesota Geotechnical Society, pp. 165–185, Minneapolis, MN, USA, February 2010.

[8] D. Kinet, K. Chah, A. Gussarov et al., "Proof of concept for temperature and strain measurements with fiber bragg gratings embedded in supercontainers designed for nuclear waste storage," IEEE Transactions on Nuclear Science, vol. 63, no. 3, pp. 1955–1962, 2016.

[9] M. Debiquy, D. Lahem, A. Bueno-Martinez, G. Ravet, J. M. Renoirt, and C. Caucheteur, "Review of the use of the optical fibers for safety applications in tunnels and car parks: pollution monitoring, fire and explosive gas detection," in Sensing Technology: Current Status and Future Trends III, pp. 1–24, Springer, Berlin, Germany, 2015.

[10] W. A. Take, D. J. White, K. H. Bowes, and N. A. Moss, "Remote real-time monitoring of tunneling-induced settlement using image analysis," in Geotechnical Aspects of Underground Construction in Soft Ground, pp. 771–777, Taylor and Francis Group, London, UK, 2006.

[11] C. Bo, Z. Peng, Z. Da, and C. Junliang, "The complex alarming event detecting and disposal processing approach for coal mine safety using wireless sensor network," International Journal of Distributed Sensor Networks, vol. 8, no. 11, 2012.

[12] M. Li and Y. Liu, "Underground coal mine monitoring with wireless sensor networks," ACM Transactions on Sensor Networks, vol. 5, no. 2, p. 10, 2009.

[13] W. Chen, X. Jiang, X. Li, J. Gao, X. Xu, and S. Ding, "Wireless sensor network nodes correlation method in coal mine tunnel based on Bayesian decision," Measurement, vol. 46, no. 8, pp. 2335–2340, 2013.

[14] A.-C. Adoko, Y.-Y. Jiao, L. Wu, H. Wang, and Z.-H. Wang, "Predicting tunnel convergence using multivariate adaptive regression spline and artificial neural network," Tunnelling and Underground Space Technology, vol. 38, pp. 368–376, 2013.

[15] C. Xiao, X. Wang, and H. Wang, "Displacement-based estimation of the best time for secondary lining construction using grey model GM (1, 1)," Geotechnical and Geological Engineering, vol. 37, no. 3, pp. 1343–1355, 2019.

[16] E. J. Ding and Z. K. Zhao, "Research advances and prospects of mine internet of things," Industry and Mine Automation, vol. 41, no. 5, pp. 1–5, 2015, in chinese.

[17] Q. Zhang, T. Pan, and H. Wang, "Research of coal mine safety management platform based on internet of things," Industry and Mine Automation, vol. 41, no. 10, pp. 49–51, 2015, in chinese.

[18] Technical Specification of Railway Tunnel Monitoring Measurement (TB 10121-2007), in Chinese.

[19] Regulations for Construction Monitoring of Foundation Pit Engineering (DG/TJ08-2001—2006), in Chinese.

[20] Technical Specification for Monitoring Construction Foundation Pit (GB 50497—2009), in Chinese.

[21] Technical Specification for Monitoring Underground Engineering of Shenzhen Urban Rail Transit (QB/SZMC-10102-2010), in Chinese.

[22] Technical Specification for Foundation Pit Engineering in Shanghai (DG/TJ08-61-2010), in Chinese.

[23] Q. H. Qian and X. L. Rong, "State issues and relevant recommendations for security risk management of China’s underground engineering," Chinese Journal of Rock Mechanics and Engineering, in Chinese, 2008.

[24] L. J. Tan, H. Q. Zhou, and K. S. Chen, "Discussion on technical standards," Applied Mechanics and Materials, vol. 880–883, pp. 1127–1133, 2014.

[25] Technical Specifications For Construction Of Highway Tunnel (JTG F60-2009), in Chinese.
[26] C. N. Ghosh and A. K. Ghose, “Estimation of critical convergence and rock load in coal mine roadways: An approach based on rock mass rating,” Geotechnical and Geological Engineering, vol. 10, no. 3, pp. 185–202, 1992.

[27] P. Altonyan and D. Taljaard, “Developments in controlling the roof in South African coal mines—a smarter approach,” Journal of the Southern African Institute of Mining and Metallurgy, vol. 101, no. 1, pp. 33–40, 2001.

[28] N. Canbulat and J. N. Merwe Van. “Design of optimum roof support systems in South African collieries using a probabilistic design approach,” Journal of the Southern African Institute of Mining and Metallurgy, vol. 109, no. 2, pp. 71–88, 2009.

[29] E. McHugh and S. Signer, “Roof bolt response to shear stress: laboratory analysis,” in Proceedings of the 18th International Conference on Ground Control in Mining, pp. 232–238, Morgantown, WV, USA, August 1999.

[30] R. J. Mainstone, “Vibrating-wire strain gauge for use in long-term tests on structures,” Engineering, vol. 176, pp. 850–855, 1953.

[31] N. Davidenkov, “Vibrating wire method of measuring deformations,” Proceedings, ASTM, vol. 34, p. 2, 1934.

[32] J.-P. Yang, W.-Z. Chen, M. Li, X.-J. Tan, and J.-X. Yu, “Structural health monitoring and analysis of an underwater TBM tunnel,” Tunnelling and Underground Space Technology, vol. 82, pp. 235–247, 2018.

[33] P. Moyo, “Structural performance monitoring and health assessment of highway bridges (Doctoral dissertation, Nanyang Technological University, School of Civil and Environmental Engineering). developing structural monitoring systems for shield driven tunnels,” HERON, vol. 48, pp. 65–78, 2002.

[34] K. O. Hill, Y. Fujii, D. C. Johnson, and B. S. Kawasaki, “Photosensitivity in optical fiber waveguides: application to reflection filter fabrication,” Applied Physics Letters, vol. 32, no. 10, pp. 647–649, 1978.

[35] Q. Wu, Y. Semenova, P. Wang, A. M. Hatta, and G. Farrell, “Experimental demonstration of a simple displacement sensor based on a bent single-mode multimode single-mode fiber structure,” Measurement Science and Technology, vol. 22, no. 2, Article ID 25203, 2011.

[36] H. Mohamad, P. J. Bennett, K. Soga et al., “Monitoring tunnel deformation induced by close-proximity bore tunneling using distributed optical fiber strain measurements,” in Proceedings of the 7th FMGM 2007: Field Measurements in Geomechanics, pp. 1–13, Boston, MA, USA, September 2007.

[37] L. L. K. Cheung, K. Soga, P. J. Bennett, Y. Kobayashi, B. Amaya, and P. Wright, “Optical fibre strain measurement for tunnel lining monitoring,” Proceedings of the Institution of Civil Engineers—Geotechnical Engineering, vol. 165, no. 3, pp. 119–130, 2010.

[38] L. Danisch, A. Chrzanowski, J. Bond, and M. Bazanowski, “Fusion of geodetic and MEMS sensors for integrated monitoring and analysis of deformations,” in Proceedings of the 13th FIG International Symposium on Deformation Measurements and Analysis, pp. 12–15, Lisbon, Portugal, May 2008.

[39] K. Rollins, T. Gerber, and C. Cummins, “Monitoring displacement vs. depth in lateral pile load tests using shape accelerometer arrays,” in Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering, vol. 5, pp. 2016–2019, Alexandria, Egypt, October 2009.

[40] D. R. Coutts, J. Wang, and J. G. Cai, “Monitoring and analysis of results for two strutted deep excavations using vibrating wire strain gauges,” Tunnelling and Underground Space Technology, vol. 16, no. 2, pp. 87–92, 2001.

[41] M. Batten, W. Powrie, R. Boorman, H.-T. Yu, and Q. Leiper, “Use of vibrating wire strain gauges to measure loads in tubular steel props supporting deep retaining walls,” Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, vol. 137, no. 1, pp. 3–13, 1999.

[42] K. J. Bakker, Soil retaining structures: development of models for structural analysis, Ph.D. thesis, Delft University of Technology, Delft, Netherlands, 2000.

[43] W. Linder, Digital Photogrammetry: Theory and Applications, Springer Science & Business Media, Berlin, Germany, 2013.

[44] B. P. Wrobel, “Photogrammetric computer vision—statistics,” Geometry, Orientation and Rec, Springer International Publish, Cham, Switzerland.

[45] K. Ikeuchi, Computer Vision: A Reference Guide, Springer, Berlin, Germany, 2014.

[46] R. Szelisky, Computer Vision: Algorithms and Applications, Springer, Berlin, Germany, 2011.

[47] N. J. McCormick and J. D. Lord, “Practical in situ applications of DIC for large structures,” Applied Mechanics and Materials, vol. 24-25, pp. 161–166, 2010.

[48] S. Yoneyma and H. Ueda, “Bridge deflection measurement using digital image correlation with camera movement correction,” Materials Transactions, vol. 53, no. 2, pp. 285–290, 2012.

[49] D. J. White, W. A. Take, and M. D. Bolton, “Measuring soil deformation in geotechnical models using digital images and PIV analysis,” in Proceedings of the 10th International Conference on Computer Methods and Advances in Geomechanics, vol. 1, pp. 997–1002, Tucson, AZ, USA, January 2001.

[50] D. J. White, W. A. Take, M. D. Bolton, and S. E. Munachen, “A deformation measurement system for geotechnical testing based on digital imaging, close-range photogrammetry, and PIV image analysis,” in Proceedings of the International Conference on Soil Mechanics and Geotechnical Engineering, vol. 1, pp. 539–542, Istanbul, Turkey, August 2001.

[51] M. Alhaddad, Photogrammetric Monitoring of Cast-iron Tunnels and Applicability of Empirical Methods for Damage Assessment, University of Cambridge, Cambridge, UK, 2016.

[52] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: a survey,” Computer Networks, vol. 38, no. 4, pp. 393–422, 2002.

[53] P. Rawat, K. D. Singh, H. Chauouchi, and J. M. Bonnin, “Wireless sensor networks: a survey on recent developments and potential synergies,” The Journal of Supercomputing, vol. 68, no. 1, pp. 1–48, 2014.

[54] D. V. Queiroz, M. S. Alencar, R. D. Gomes, I. E. Fonseca, and C. Benavente-Peces, “Survey and systematic mapping of industrial wireless sensor networks,” Journal of Network and Computer Applications, vol. 97, pp. 96–125, 2017.

[55] S. Nithyakalyani and S. S. Kumar, “Data relay clustering algorithm for wireless sensor networks: a data mining approach,” Journal of Computer Science, vol. 8, no. 3, pp. 1281–1284, 2012.

[56] M. Munizj, A. T. Siddiqui, and M. Rahul, “An improved data mining technique and online mining for energy efficiency in wireless sensor networks: a comparative review,”
K. K. Chintalapudi, S. I. G. Bluetooth, "Specification of the Bluetooth system," Wireless Communications, vol. 7, no. 7, 2016.

G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," IEEE Journal on Selected Areas in Communications, vol. 18, no. 3, pp. 535–547, 2000.

P. Kinney, "Zigbee technology: wireless control that simply works," Communications Design Conference, vol. 2, pp. 1–7, 2003.

M. A. Moridi, Y. Kawamura, M. Sharifzadeh, E. K. Chanda, and H. Jang, "An investigation of underground monitoring and communication system based on radio waves attenuation using ZigBee," Tunnelling and Underground Space Technology, vol. 43, pp. 362–369, 2014.

M. A. Moridi, Y. Kawamura, M. Sharifzadeh, E. K. Chanda, M. Wagner, and H. Okawa, "Performance analysis of ZigBee network topologies for underground space monitoring and communication systems," Tunnelling and Underground Space Technology, vol. 71, pp. 201–209, 2018.

K. K. Chintalapudi, Design of Wireless Sensor Network Based Structural Health Monitoring Systems, University of Southern California, Los Angeles, CA, USA, 2006.

J. P. Lynch, "An overview of wireless structural health monitoring for civil structures," Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 365, no. 1851, pp. 345–372, 2006.

S. N. Pakzad, G. L. Fenves, S. Kim, and D. E. Culler, "Design and implementation of scalable wireless sensor network for structural monitoring," Journal of Infrastructure Systems, vol. 14, no. 1, pp. 89–101, 2008.

Y. Bao, J. L. Beck, and H. Li, "Compressive sampling for accelerometer signals in structural health monitoring," Structural Health Monitoring, vol. 10, no. 3, pp. 235–246, 2011.

G. Quer, R. Masiero, G. Pillonetto, M. Rossi, and M. Zorzi, "Sensing, compression, and recovery for WSNs: sparse signal modeling and monitoring framework," IEEE Transactions on Wireless Communications, vol. 11, no. 10, pp. 3447–3461, 2012.

M. F. Duarte, G. Shen, A. Ortega, and R. G. Baraniuk, "Signal compression in wireless sensor networks," Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 370, no. 1958, pp. 118–135, 2012.

T. Nagayama and B. F. Spencer Jr., "Structural health monitoring using smart sensors," Newmark Structural Laboratory Report Series (NSEL Report Series ISSN 1940–9826), University of Illinois at Urbana-Champaign, Urbana, IL, USA, 2007.

Y. Bao, H. Li, X. Sun, Y. Yu, and J. Ou, "Compressive sampling-based data loss recovery for wireless sensor networks used in civil structural health monitoring," Structural Health Monitoring: An International Journal, vol. 12, no. 1, pp. 78–95, 2013.

C. Y. Kim, G. J. Bae, S. W. Hong, C. H. Park, H. K. Moon, and H. S. Shin, "Neural network based prediction of ground surface settlements due to tunneling," Computers and Geotechnics, vol. 28, no. 6-7, pp. 517–547, 2001.

H. Wu, Y. J. Zhong, W. Xu, W. Shi, and X. H. Shi, "Experimental investigation of ground and air temperature fields of a cold-region road tunnels in NW China," Advances in Civil Engineering, vol. 2020, Article ID 4732490, 12 pages, 2020.

M. R. Moghaddasi and M. Noorian-Bidgoli, "ICA-ANN, ANN and multiple regression models for prediction of surface settlement caused by tunneling," Tunnelling and Underground Space Technology, vol. 79, pp. 197–209, 2018.

X. Liu, L. Yang, X. Zhang, and L. Wang, "A model to predict crosscut stress based on an improved extreme learning machine algorithm," Energies, vol. 12, no. 5, p. 896, 2019.

C. Lian, Z. Zeng, W. Yao, and H. Tang, "Displacement prediction model of landslide based on a modified ensemble empirical mode decomposition and extreme learning machine," Natural Hazards, vol. 66, no. 2, pp. 759–771, 2013.

Y. Kang, X. Li, Y. Lu, and C. Yang, "Application of chaotic phase space reconstruction into nonlinear time series prediction in deep rock mass," in Proceedings of the 2008 Fifth International Conference on Fuzzy Systems and Knowledge Discovery, vol. 5, pp. 593–597, Jinan, China, October 2008.

H. B. Liu, Y. Y. Sun, Y. C. Cheng, P. Jiang, and Y. B. Jiao, "The deformation prediction of foundation pit slope based on time series analysis," Applied Mechanics and Materials, vol. 80-81, pp. 516–520, 2011.

C.-H. Chen, L. Wu, and Y.-X. Peng, "The analysis method of rock mass deformation of large cross-section tunnel," Geotechnical and Geological Engineering, vol. 34, no. 2, pp. 739–743, 2016.

S. Yagiz, C. Gokceoglu, E. Sezer, and S. Iplikci, "Application of two non-linear prediction tools to the estimation of tunnel boring machine performance," Engineering Applications of Artificial Intelligence, vol. 22, no. 4-5, pp. 808–814, 2009.

A. Mottahedi, F. Sereshki, and M. Ataei, "Overbreak prediction in underground excavations using hybrid ANFIS-PSO model," Tunnelling and Underground Space Technology, vol. 80, pp. 1–9, 2018.

L. T. Nguyen and T. Nestorović, "Unscented hybrid simulated annealing for fast inversion of tunnel seismic waves," Computer Methods in Applied Mechanics and Engineering, vol. 301, pp. 281–299, 2016.

J. Guo, F. Yang, G. Enrner, and J. Yang, "Tracking analysis and improvement of broadband Kalman filter using the two-echo-path model as a rapid tunnel," in Proceedings of the 2018 16th International Workshop on Acoustic Signal Enhancement (IWAENC), pp. 341–345, Tokyo, Japan, September 2018.

J. Ji, Q. Tong, L. Wang et al., "Application of the EnKF method for real-time forecasting of smoke movement during tunnel fires," Advances in Engineering Software, vol. 115, pp. 398–412, 2018.

M. Fayaz, I. Ullah, and D.-H. Kim, "Underground risk index assessment and prediction using a simplified hierarchical fuzzy logic model and kalman filter," Processes, vol. 6, no. 8, p. 103, 2018.

Z. Zhang, F. Sun, and B. Chen, "Thermal-mechanical coupled analysis for tunnel lining with circular openings," Tunnelling and Underground Space Technology, vol. 102, Article ID 103, 2020.

W. Gao, "Integrated intelligent method for displacement prediction in underground engineering," Neural Processing Letters, vol. 47, no. 3, pp. 1055–1075, 2018.

L. Zhu, T. Huang, Y. Q. Shen, and X. M. Zeng, "Study on tunnel settlement prediction method based on parallel grey neural network model," in Proceedings of the International Conference on Intelligent Earth Observing and Applications 2015, vol. 9808, p. 98082B, Guilin, China, October 2015.
[88] Z.-D. Cui and S.-X. Ren, "Prediction of long-term settlements of subway tunnel in the soft soil area," *Natural Hazards*, vol. 74, no. 2, pp. 1007–1020, 2014.

[89] L. Li, Y. Qiang, S. Li, and Z. Yang, "Research on slope deformation prediction based on fractional-order calculus gray model," *Advances in Civil Engineering*, vol. 2018, Article ID 9526216, 9 pages, 2018.

[90] T. I. Boubez and R. L. Peskin, "Wavelet neural networks and receptive field partitioning," in *Proceedings of the IEEE International Conference on Neural Networks*, pp. 1544–1549, San Francisco, CA, USA, April 1993.

[91] T. Yamakawa, E. Uchino, and T. Samatsu, "Wavelet neural networks employing over-complete number of compactly supported non-orthogonal wavelets and their applications," in *Proceedings of 1994 IEEE International Conference on Neural Networks (ICNN'94)*, vol. 3, pp. 1391–1396, Orlando, FL, USA, July 1994.

[92] T. Wang and Y. Sugai, "A wavelet neural network for the approximation of nonlinear multivariable functions," *IEEE Transactions on Electronics, Information and Systems*, vol. 120, no. 2, pp. 185–193, 2000.

[93] Y. Chen, B. Yang, and J. Dong, "Time-series prediction using a local linear wavelet neural network," *Neurocomputing*, vol. 69, no. 4–6, pp. 449–465, 2006.

[94] T. Wang and Y. Sugai, "A local linear adaptive wavelet neural network," *IEEE Transactions on Electronics, Information and Systems*, vol. 122, no. 2, pp. 277–284, 2002.

[95] A. Majdi and M. Beiki, "Evolving neural network using a genetic algorithm for predicting the deformation modulus of rock masses," *International Journal of Rock Mechanics and Mining Sciences*, vol. 47, no. 2, pp. 246–253, 2010.

[96] S. Suwansawat and H. H. Einstein, "Artificial neural networks for predicting the maximum surface settlement caused by EPB shield tunneling," *Tunnelling and Underground Space Technology*, vol. 21, no. 2, pp. 133–150, 2006.

[97] G.-B. Huang, "Learning capability and storage capacity of two-hidden-layer feedforward networks," *IEEE Transactions on Neural Networks*, vol. 14, no. 2, pp. 274–281, 2003.

[98] L. Muduli, P. K. Jana, and D. P. Mishra, "Wireless sensor network based fire monitoring in underground coal mines: a fuzzy logic approach," *Process Safety and Environmental Protection*, vol. 113, pp. 435–447, 2018.

[99] M. F. Othman and K. Shazali, "Wireless sensor network applications: a study in environment monitoring system," *Procedia Engineering*, vol. 41, pp. 1204–1210, 2012.

[100] P. K. Mishra, M. Pratik, M. Kumar, S. Kumar, and P. K. Mandal, "Wireless real-time sensing platform using vibrating wire-based geotechnical sensor for underground coal mines," *Sensors and Actuators A: Physical*, vol. 269, pp. 212–217, 2018.

[101] J. L. Qiu, Y. Q. Lu, J. X. Lai, Y. W. Zhang, T. Yang, and K. Wang, "Experimental study on the effect of water gushing on loess metro tunnel," *Environmental Earth Sciences*, vol. 79, no. 11, pp. 1–12, 2020.

[102] H.-S. Yun, G.-J. Song, Y.-B. Kim, C.-Y. Kim, and Y.-S. Seo, "Developments of real-time monitoring system to measure displacements on face of tunnel in weak rock," *Journal of Korean Tunnelling and Underground Space Association*, vol. 17, no. 4, pp. 441–455, 2015.

[103] R. Han, W. Yang, and K. You, “MB-OFDM-UWB based wireless multimedia sensor networks for underground coalmine: a survey,” *Sensors*, vol. 16, no. 12, p. 2158, 2016.

[104] L. Atzori, A. Iera, and G. Morabito, "The internet of things: a survey," *Computer Networks*, vol. 54, no. 15, pp. 2877–2895, 2010.

[105] D. Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, "Internet of things: vision, applications and research challenges," *Ad Hoc Networks*, vol. 10, no. 7, pp. 1497–1516, 2012.

[106] C. Zhou and L. Y. Ding, "Safety barrier warning system for underground construction sites using internet-of-things technologies," *Automation in Construction*, vol. 83, pp. 372–389, 2017.

[107] B. Jo and R. Khan, "An internet of things system for underground mine air quality pollutant prediction based on azure machine learning," *Sensors*, vol. 18, no. 4, p. 930, 2018.

[108] Y. Wu, M. Chen, K. Wang, and G. Fu, "A dynamic information platform for underground coal mine safety based on internet of things," *Safety Science*, vol. 113, pp. 9–18, 2019.

[109] B. Jo, R. M. A. Khan, Y. S. Lee, J. H. Jo, and N. Saleem, "A fiber Bragg grating-based condition monitoring and early damage detection system for the structural safety of underground coal mines using the Internet of things," *Journal of Sensors*, vol. 2018, Article ID 9301873, 16 pages, 2018.

[110] B. Jo, R. Khan, and Y.-S. Lee, "Hybrid blockchain and internet-of-things network for underground structure health monitoring," *Sensors*, vol. 18, no. 12, p. 4268, 2018.

[111] L. Y. Ding, C. Zhou, Q. X. Deng et al., "Real-time safety early warning system for cross passage construction in Yangtze riverbed metro tunnel based on the internet of things," *Automation in Construction*, vol. 36, pp. 25–37, 2013.

[112] X. L. Wang, S. Y. He, J. X. Lai, R. S. Garnes, and Y. Zhang, "Karst geology and mitigation measures for hazards during metro system construction in Wuhan, China," *Natural Hazards*, vol. 102, no. 3, pp. 1909–1935, 2020.

[113] J. L. Qiu, Y. Q. Lu, J. X. Lai, C. X. Guo, and K. Wang, "Failure behavior investigation of loess metro tunnel under local-high-pressure water environment," *Engineering Failure Analysis*, vol. 112, no. 4, 2020.

[114] Y. Wei, J. Huang, and S. Liang, "Measurement and modeling concrete creep considering relative humidity effect," *Mechanics of Time-Dependent Materials*, vol. 24, no. 1, pp. 1–17, 2020.

[115] T. Liu, Y. J. Zhong, Z. L. Han, and W. Xu, "Deformation characteristics and countermeasures for a tunnel in difficult geological environment in NW China," *Advances in Civil Engineering*, vol. 2020, Article ID 1694821, 16 pages, 2020.

[116] Z. Zhou, Y. Dong, P. Jiang, D. Han, and T. Liu, "Calculation of pile side friction by multiparameter statistical analysis," *Advances in Civil Engineering*, vol. 2019, Article ID 2638520, 9 pages, 2019.

[117] H. Sun, Q. P. Wang, P. Zhang, Y. J. Zhong, and X. B. Yue, "Spatiotemporal characteristics of tunnel traffic accidents in China from 2001 to present," *Advances in Civil Engineering*, vol. 2019, Article ID 4536414, 16 pages, 2019.

[118] X. X. Nie, S. S. Feng, S. D. ZHang, and Q. Gan, "Simulation study on the dynamic ventilation control of single head roadway in high-altitude mine based on thermal comfort," *Advances in Civil Engineering*, vol. 2019, Article ID 2973504, 12 pages, 2019.

[119] H. Wu, C. K. Yao, C. H. Li et al, "Review of application and innovation of geotextiles in geotechnical engineering," *Materials*, vol. 13, 2020.

[120] C. Liu, L. Xing, H. W. Liu et al., "Numerical study of bond slip between section steel and recycled aggregate concrete with full replacement ratio," *Applied Sciences*, vol. 10, no. 3, Article ID 887, 2020.
[121] X. G. Yu, G. H. Xing, and Z. Q. Chang, "Flexural behavior of reinforced concrete beams strengthened with near-surface mounted 7075 aluminum alloys bars," Journal of Building Engineering, vol. 31, 2020.

[122] Z. Q. Zhang and F. Sun, "Thermal-mechanical coupled analysis for tunnel lining with circular openings," Tunnelling and Underground Space Technology, vol. 97, Article ID 103409, 2020.

[123] Z. Q. Zhang, K. J. Zhang, W. J. Dong, and B. Zhang, "Study of rock-cutting process by disc cutters in mixed ground based on three dimensional particle flow model," Rock Mechanics and Rock Engineering, vol. 53, no. 6, 2020.

[124] Z. F. Wang, S. L. Shen, G. Modoni, and A. N. Zhou, "Excess pore water pressure caused by the installation of jet grouting columns in clay," Computers and Geotechnics, vol. 125, Article ID 103667, 2020.