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Recent advances of digitization in rock mechanics and rock engineering

Hehua Zhu*, Xiaojun Li, Xiaoying Zhuang

Key Laboratory of Geotechnical Engineering, Department of Geotechnical Engineering, Tongji University, Shanghai, 200092, China

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Abstract: In recent years, there are growing demands of representing rock mechanics and rock engineering in a digital format that can be easily managed, manipulated, analyzed and shared. The objective of this paper is to give a comprehensive review of the status quo and future trends of digitization in rock mechanics and rock engineering. Research topics essential to the process of digitization are firstly discussed, including data acquisition, data standardization, geological modeling, visualization and digital-numerical integration. New techniques that will play an important role in digitization process but require further improvement are then briefly proposed. Finally, achievements of present methods and techniques for digitization in substantial rock mechanics and rock engineering are presented.

Key words: information digitization; rock mechanics and rock engineering; digital tunnel; digital-numerical integration

1 Introduction

Rocks are naturally mineral aggregates with prominent properties of uncertainty, anisotropy and inhomogeneity, making their mechanical behaviors difficult to be accurately predicted. Consequently, geological conditions in most cases are too complicated to be clearly understood in advance. Compared with engineering constructions above the ground, the management and construction of underground engineering are faced with more challenges and high risks. To better understand these problems, there are growing demands in recent years of representing rock mechanics and rock engineering in a digital format for efficient and cost-effective management, manipulation, analysis and accessibility. For example, a virtual environment reproducing results of indoor or in-situ rock tests can help to establish numercial models and to study the mechanical behaviors of rocks. Besides, engineers require a realtime digital platform to manage engineering data during construction and the project as a whole in an efficient way so that the construction risk level can be reduced.

Since the 1990s, efforts have been devoted to the digitization of rock engineering for addressing some field-specific problems. The concept of digital strata was firstly introduced by Zhu [1] as a visualized representation of original and construction-disturbed strata information. It was further developed into 3D strata information system [2] to facilitate the integration of engineering data, enhance the level of data visualization, and improve the efficiency in decision-making. Li et al. [3] proposed that the digitization of underground engineering is to effectively manage the data involved in underground construction process and provide an information sharing and analysis platform for lifecycle information of underground engineering. A comprehensive concept of digital underground space and engineering (DUSE) was later proposed by Zhu and Li [4], and its basic framework was defined in terms of engineering, information, services and software architecture. Wu et al. [5] proposed the idea of digital mine, an integrated control and management system based on computer network, digitization, virtualization and integration. A similar concept of digital oilfield was proposed for Daqing Oilfield [6].

Despite these efforts, digitization in rock mechanics and rock engineering is a relatively new research field. Information techniques such as data acquisition, data standardization, database, networking and visualization are involved in the process of digitization, and new methods such as photogrammetry and wireless sensor network are on the list waiting for further development.

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*Corresponding author. Tel: +86-21-65985014;
E-mail: zhuhehua@mail.tongji.edu.cn

2 Key techniques of digitization

Digitization provides the basis for the analysis of multimedia and intelligent technology, and serves as the basis of information community between scientific research and engineering practice. Some generally recognized techniques of digitization in rock mechanics and rock engineering include data acquisition, data standardization, model reconstruction and visualization, digital-numerical integration, data mining and integrated platform. In an idealized digital environment, various parameters in construction and test are firstly obtained through data acquisition, providing basic information basis for modeling, computation and analysis. These parameters are expressed in a standard format so that the efficiency of acquisition, storage and sharing can be improved. Then a virtual model is reconstructed and visualized in a digital system, in which engineering data are managed digitally. The virtual model is further analyzed by digital-numerical integration and artificial intelligence system to provide supports in decision-making. Finally, combining with geographic information system (GIS), all these digital models and methods are integrated in a digital platform so that engineering information can be acquired, stored, managed, shared, computed and analyzed in an integrated, comprehensive and dynamic environment. As a result, the traditional field of rock mechanics and rock engineering is transformed into a digital and intelligent one.

2.1 Data standardization

Information gaps and inefficient data exchange are the common defects in engineering construction, making it difficult to integrate data information from different sectors or even the same sector. Early in the 1980s, Greenwood [7] showed the significance and role of standardization of data exchange format that would take place in geotechnical engineering. The implication of standardization was recently revealed in data collection and processing of rock model tests [8–11]. In standardization of monitoring and remote sensing data, sensor model language (SensorML) and transducer markup language (TransducerML) are the dominant methods at present. For digitization of rock mechanics test data, standardization can help to realize the storage of test data on web server in a standard format so that they are accessible to remote users all over the world. Test data can be shared, used and maintained effectively. The recognized standardizations of test data format at present are the geotechnical exchange format (GEF) and the data interchange for geotechnical and geoenvironmental specialists (DIGGS). The three international geo-engineering societies, namely, the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), the International Association for Engineering Geology and Environment (IAEG), and the International Society for Rock Mechanics (ISRM) have jointly set up the Technical Committee 2, devoting to the development of geotechnical markup language (GeotechML) based on GML, a specialization of extendable marking language (XML) for the digitization of data in geological engineering [12]. The committee has been developing a system of standards for drilling data and soil test data. However, the study on digitization of underground construction is still at its beginning. Research on digital strata and digital underground space has been carried out in the past few years and digital underground engineering is the current focus, including standardization of basic engineering information and information from all parts of a project. Data standardization of underground engineering will continue to be the topic attracting interests from researchers and engineers in this field for a long period of time. It will greatly promote the development of data acquisition, storage, sharing and efficient application in rock mechanics and rock engineering.

2.2 Data acquisition

Data acquisition can be mainly divided into two types, direct acquisition and indirect acquisition. Direct data acquisition is the process by which various physical parameters measured are transformed into electrical signals by the sensors, and then converted to digital format through signal conditioning, sampling, quantization, coding and transmission for processing or storage by a computer. Data acquisition system can provide a flexible user-defined system for measurement by utilizing hardware and software. Indirect data acquisition involves the collection and processing of existing project data, such as texts, drawings, images, sounds, etc. In the following, we will focus on the direct data acquisition.

The technology of direct data acquisition is widely used in various fields. In the field of rock mechanics and rock engineering, traditional data acquisition technologies include water-level elevation measurement, transiting instrument measurement, theodolite measurement, steel scale measurement, stadia survey, electromagnetic distance measurement, GPS measurement, sensor measurement, acoustic and ultrasonic detection technology, geological radar detection technology, etc. These traditional techniques have unique advantages for specific engineering problems and have grown mature in practical applications.

In recent years, with the rapid development of computer technology, sensor technology and communication technology, some new data acquisition techniques have been widely applied, and particularly, the digital imaging and wireless sensor networks have great potential development in rock mechanics and rock engineering. They have shown advantages in substantial projects and are gradually getting mature. However, some new issues and difficulties arise in the application of data acquisition technology to rock mechanics and rock engineering. These are the topics for further studies.

2.3 3D modeling based on digitization

To replace material flow by fast information flow is the prominent feature in this information era. In the construction of information systems, especially those containing a huge amount of geological spatial data, it is of great necessity to visualize geological objects in three dimensions. Whether in mining resources assessment, oil drilling exploration and development of water resources and hydropower projects or in the utilization and management of underground space, it is always needed to express a series of data with strong three-dimensional (3D) spatiality. Dull data or two-dimensional (2D) planar representation for a complex structure object can be too abstract or confusing for users to understand. 3D geological modeling can solve this problem by realizing visualization of objects and demonstrating a vivid underground space.

The reconstruction of 3D model includes the reconstruction of both a complex geological unit and artificial structures inside or above the geological body. A man-made structure possesses spatial characteristics, which are well known, standard and accurate although the information of the characteristics can be huge in amount. With currently available visualization techniques, in most cases it is not a difficult task to reconstruct the 3D model of a man-made structure. For geological units, due to their complexity in information sources, spatial relations and uncertainties, the reconstruction techniques remain to be solved in rock mechanics and rock engineering. 3D geological modeling is a basic work in the scope of geosciences study as well as a core technology in the fields of geological engineering, geotechnical engineering and 3D-GIS engineering. 3D geological modeling is a technique where spatial information management, geological interpretation, spatial analysis and prediction, geological statistics, entity content analysis, image visualization and other tools are integrated on a 3D digital platform for geological analysis by computer technologies. How to make the invisible and complicated underground space “transparent” by using 3D geological modeling becomes an urgent task.

Since the 1980s, many geological models have been employed to represent geological bodies. Approaches of 3D geological modeling developed so far can be mainly classified into three categories: discrete point source method, profile framework method and multi-source data coupled modeling method. The essence of geological modeling is a process from sampling of physical geological unit to digital modeling, and then to 3D visualization [13]. Raper [14–16] classified geological objects into two types, i.e. sampling limited object and definition limited object. The former refers to a natural object whose morphology is only determined by the quantity of sampling data, such as rock stratum or fault plane. While a definition limited object refers to a natural object whose morphology depends on personal judgment. For example, a stratum can be classified according to the fossil composition and the variation characteristics of rocks. Though a geological space found in the real world possesses certain properties, it appears to be uncertain due to the limitation of human knowledge. From the point of view of definition limited object, if the classification standards are subdivided into different levels or resolutions, the features of a geological object will be certain under such standards. The uncertainties of spatial relationship and attributes of geological objects are due to insufficient sampling or sampling under limited conditions. Theoretically, for geological objects such as rock stratum or fault plane, a complete understanding of the object can be achieved by taking infinite geological samples. Geological sampling is the most effective way to recognize underground space. For example, with a limit number of geological sampling points and based on geological engineers’ experiences, geological features of a site can be obtained. Then geological structure modeling is used to fit a 3D surface, which can reflect strata distribution in the way according to the point data of geological strata revealed by geological sampling data, and realize the representation of geological objects. A geological model can be built, showing the spatial geometry, attributes and relations of a geological unit from the geological constraints imposed by geological samples. A unified geological model can be expressed as $M^n(\Omega, N, \varphi, c)$ [17], where Ω is the unit collection of discrete geological model, N is the topological adjacency relations between elements in Ω, φ is the attribute information of geological object, and c is the geological constraints imposed by geological samples.

Geological constraints are critical for the establishment of geological model. Mallet [17] classified them into two categories: hard constraints and soft constraints. Hard constraints can be subdivided into equal hard constraints and unequal hard constraints. Li et al. [18] divided the geological data into three categories according to reliability, i.e. deterministic data, knowledge inference and uncertainty data. Deterministic data include borehole data, boundary information of lithology obtained through borehole sampling, and attribute characteristics such as physico-mechanical characteristics of stratum. Examples of knowledge inference are contour map for coal seam floor and geological map of sections, which are usually obtained by geological interpretation or geological engineers' experiences based on borehole data and seismic data. Uncertainty data are basically gained by means of subjective interpretation, interpolation and extrapolation such as spatial variation in rock thickness and attribute information without sampling points.

2.4 Visualization

3D visualization, virtual reality and augmented reality are important in rock mechanics and rock engineering. 3D visualization provides an easy way to understand information by displaying data in 3D graphics. Graphics enhanced by virtual reality technology creates a vivid, realistic and realtime interactive virtual environment by computer. Augmented reality is a further development of virtual reality, which greatly simplifies the modeling process and removes unnecessary work by making use of real scenes. It can provide a more realistic and realtime interaction with the real world. 3D visualization can be regarded as a process of representing abstract data in a visual way. Compared with 3D visualization, virtual reality technology is a process to simulate the real world by computer while augmented reality is an advanced technology, which can improve the integration between the virtual world and the real world.

2.4.1 *Virtual reality technology*

The visualization technology in civil engineering uses virtual reality to create a 3D graphic image reflecting realtime changes and interactions of entity objects [19]. Through lifelike perceptions of vision, hearing, touching and smelling, the users feel as if being in a real world. Virtual reality technology, network and multimedia are known as the three most promising technologies in the 21st century. The distinct features of virtual reality technology are "3I": interactivity, imagination and immersion. It is the keystone and trend in the development of simulation technology in rock engineering.

The main purpose of 3D visualization and virtual reality technology is to enhance the acquisition and understanding of massive information. However, if the information and data are just displayed in a 3D graphic environment, the effect may not be perfect and sometimes it can even bring negative effects. Therefore, it is necessary to carry out in-depth studies on the organization and browsing methods of information in 3D space according to the characteristics of underground space and engineering [4].

2.4.2 *Augmented reality technology*

The development of augmented reality technology benefits from the rapid development of computer graphics technology in the 1990s. In recent years, it has become a research topic for many famous universities and research institutions all over the world. With the help of optical display technology, interactive technology, multi-sensor technology, computer graphics and multimedia technology, it integrates the computer-generated virtual environment with the real scenes, making the user believe that the virtual environment is a part of the real scene around him/her [20].

The real and virtual environments should be well integrated as a single augmented environment, thus virtual objects need to be accurately added to the location of the real environment. This process is called "registration", which is a major challenge in the development of augmented reality technology at present. In reality, the head movement of the user and the movement of tracked objects will have influences on the registration. In order to get accurate registration, many realtime tracking methods have been employed, including visual tracking, inertial tracking, magnetic tracking, etc. Visual tracking is the most widely used method because of its high precision, easy arrangement and good adaptability to various environments.

2.5 Digital-numerical integration

In digitization process, the digital integrity between communication and computation numerical analysis, such as finite element analysis (FEA), is the key technology to make a digital platform useful for research and engineering constructions. A complete FEA is composed of several stages, including system characterization, preprocessing, computation and post-processing. Significant amount of time is spent on preprocessing and post-processing if geometric model becomes more complex. Therefore, establishing an efficient and intuitive object-oriented system of finite element discretization and results processing is extremely important [21]. When facing substantial geotechnical engineering, the processed data are vast due to complex nature of geological environment, geological structure, process of construction and load, etc. Manual input of the dull data is a time-consuming process and can easily introduce errors, which are uneasy to be checked and corrected. For this reason, the geological model is normally simplified by the simulator. However, this can impair the accuracy and reliability of the calculation results. Therefore, it is necessary to develop a method to simplify the preprocessing of FEA, i.e. digital-numerical integration technology.

Digital-numerical integration technology is a process where the complicated digital model is transformed automatically into numerical model and imported to a numerical analysis system, and “hides” behind the digital model platform.

The results of numerical analysis can be displayed intuitively by digital models. Li et al. [22] presented the concept of integration of digitization and numerical analysis based on DUSE, and adopted compound structures of embedding type and loss type for integration. In this research, the integration was discussed from three aspects: data, function and technique, and a unified organizational structure was built in terms of DUSE system and numerical analysis system. Ultimately, the implementation frame and procedures of rigorous integration system were established. In addition, by using CRM (cutting, reconstruction and meshing) technology, the geological model transforming method was proposed to realize the integration. However, the above research is still in progress now and the finite element modeling of the underground structures has not been completely included. Dong et al. [23, 24] introduced an indirect modeling method of numerical model, i.e. CDIM (cutting, densing, islands Delaunay triangulation and meshing) model transformation, which was proposed for pit foundation. Based on 3D digital models, the modeling procedures by this method are listed as follows: region cutting, point interpolation in arbitrary planar domains, multi-island and Delaunay triangulation of multi-connecting regions, automatic generation of finite element meshes, and final import of numerical model into numerical analysis system. It has been successfully applied to the simulations of 3D construction process for a underground substation in Shanghai.

Much of the research in the past stays on the integration of GIS platform and numerical analysis software [25–27]. The integration of virtual reality and numerical analysis for the automatic monitoring system of underground engineering and digital tunnel has not been investigated yet. By using virtual reality software, the construction steps and processes can be clearly displayed on computer to users. Users will be informed of realtime construction progress and able to manage various resources for construction. By using digital-numerical integration system, the existing digital models can be directly converted to preprocessing file and analyzed by numerical tools such as ANSYS and Tongji GeoFBA software. The analysis results will give the distribution of deformation and stress in each construction step, and the deformation and stress in consecutive construction steps can be predicted. It is believed that the digital-numerical integration technology will help to provide guidance for the lifecycle construction and management of underground engineering.

2.6 Artificial intelligence and data mining

Artificial intelligence (AI) can be used to develop intelligent systems, which can simulate or even extend human intelligence. AI was initially proposed in 1956 as an interdisciplinary technology developed through the crosslink between computer science, control theory, information theory, microelectronics, neurophysiology, psychology, linguistics and some other disciplines. Over the past five decades, the scope of AI has been well enriched.

Data mining is an important issue in the field of information technology. With the development of computer hardware and software, systems containing a large amount of data and information are almost ubiquitous. The values of original data lie in the potential unknown information hidden inside, which may help people make proper decision. Data mining is such a process to extract implicit, previously unknown, and potentially useful information from a set of large, incomplete, noisy, vague and random data. These information and knowledge can be expressed in terms of concepts, rules, laws and models.

As the data acquisition technology develops, the quantity and attribute of data are also growing. How to extract useful knowledge from original data is an issue that needs to be solved by data mining. Nowadays, it has become a research topic in the fields of database, information management system, AI and decision support, etc.

Data mining is a fundamental step in the process of knowledge discovery. In rock mechanics and rock engineering, in a broader sense, data mining is to find previously unknown, valid, useful information from the huge data related to the lifecycle of rock mechanics and rock engineering in database, and apply the information to the decision-making.

3 Techniques needed to be further developed

The applications of new technologies to the information digitization of rock mechanics and rock engineering are the trend of further development, including automatic identification based on digital image under the complex environment, wireless sensor network technology, intelligent integration technology composed of data acquisition, identification, modeling and analysis, 3S technologies, WebGIS and 4D GIS.

3.1 Automatic identification technology based on digital image under complex environment

Digital image technology includes digital photography and image processing techniques. It combines computer graphics, photoelectric imaging, image processing, computer vision and some other techniques. As an accurate and efficient information acquisition technology using digital camera and computer, the technology has been quickly adopted in various subjects and research fields due to its convenience and flexibility, contact-free data acquisition and simple image processing. Since the digital image is invented, it has been quickly applied to all areas of civil engineering, including roads, bridges, tunnels, industrial and civil buildings, hydraulic structures and measurement system. Now it is involved in almost all stages of the lifecycle of constructions, from planning, modeling, field test, pre-engineering survey, construction control management, and quality examination to maintenance and management in use. The technology has gradually transformed from object to subject in research and serves as a convenient tool to obtain data. Under complex underground environments, the technical bottleneck is how to collect data from the massive information and how to identify the diseases of underground engineering structures automatically.

3.2 Wireless sensor network technology

With the rapid development of semiconductor technology, sensor technology, embedded technology and communication technology, the wireless sensor network technology is more and more widely used. It has the capabilities of sensing, computation, storage and communication. A wireless sensor network (WSN) consists of a great number of wireless sensor nodes that have the same or different features. Each sensor node is composed of data acquisition module (sensor, A / D converter), data processing and control module (microprocessors, storage), communication module (wireless transceiver), power supply modules (battery, DC / AC power converter), and so on.

Data acquisition in traditional method is mostly done manually, which is inefficient, and moreover, the accuracy and reliability of the data obtained cannot be guaranteed. This is due to the fact that the data are not collected automatically and the realtime change in the structure performance is unknown. The application of digital image technology and WSN technology can address these problems by establishing a highly efficient and accurate, objective, fast and easy intelligent sensing method for maintenance and detection of rock mass structure. Compared with traditional sensor monitoring technology, the WSN has shown some outstanding merits, such as low cost and energy consumption, high precision, security and interference resistance, auto-dynamic networking and flexible deployment. In addition, it can realize realtime monitoring, perception and automatic collection of a variety of objects within the network distribution region. The information collected is processed to complete the automatic data acquisition and environmental monitoring task.

Present sensors used in rock engineering are especially designed for collecting or testing specific data such as angles of inclination or crack opening width with respect to the prescribed threshold values. From the experiences in using the WSN for tunnel fire monitoring, it is observed that the WSN performs well in collecting data and responses quickly to accidental event. However, some problems about the WSN, which remain to be solved before realizing its practical value in engineering, are listed as follows. Firstly, the communication among the sensors is sensitive to interfering electronic signals or obstacles on site, making accurate signal analysis and conditional monitoring difficult. The second problem is the cost of mircosensors because a great number of sensors are needed for analysis and monitoring with acceptable accuracies. Sustainable power supply of the network is the third problem though low in amount, to which solutions at this moment are high-energy batteries, self energy collection technique and wireless charge technique. However, none of them is satisfactory for industrial application yet. The optimal energy and cost-effective design of sensor network regarding of some controlling or concerned locations of a structure or a geological unit is the last question to be answered.

3.3 Intelligent integration technology

To achieve the information digitization of rock engineering, the first part that needs to be digitized is geological exploration and design process. The integration and application of these advanced data acquisition technologies including data standardization method, 3D GIS technology, geological modeling technology, digital-numerical integration technique, visualization, virtual reality and AI, are the key to realize the information digitization of rock engineering. Therefore, the information digitization of rock mechanics and rock engineering is a comprehensive research system, which progresses with the research advances in the technologies described above.

3.4 Application of 3S technologies

In the past, due to the lack of systematic data storage and analysis tools, many of spatial data in rock engineering cannot be used. The so-called “3S” technologies (GPS, GIS and RS) can provide a powerful tool for the positioning, acquisition, storage, display and analysis of spatial data. The 3S technologies are often integrated as a comprehensive application system, where GPS is used for realtime positioning, RS for data acquisition and updating, and GIS for spatial analysis and comprehensive treatment. An integrated system by 3S technologies can be regarded as a highly automatic, realtime GIS platform. This platform cannot only realize automatic and realtime acquisition, processing and updating of data, but also be used to analyze data to support decision-making and consultancies for various applications. Furthermore, it can also answer various complicated problems put forward by users.

3.5 Application of 3D WebGIS to the information digitization in rock engineering

After nearly thirty years’ development of GIS, particularly with the recent development of internet technology, WebGIS comes into existence. WebGIS is a computerized system for collecting, storing, processing, analyzing and displaying geographic information in the internet or intranet environment. It is the combination of internet technology, Web and traditional GIS technology. The starting point of WebGIS is to use the internet to publish geographic information and allow customers to browse and access data and services of the GIS. WebGIS provides a perfect solution to share geographic data and GIS inter-operation. WebGIS takes the advantage of the internet on the basis of the traditional desktop-based or LAN-based GIS, so it has new functions. Compared with the traditional GIS, WebGIS has the following advantages: (1) simpler operation, lower development and management costs, (2) easier to share information, (3) seamless integration with web applications, (4) platform independence, and (5) capable of balancing computational loads among different servers.

Rock mechanics and rock engineering contain a great amount of geospatial information. GIS has superior performances in processing, storing and sharing geospatial information compared with traditional or common information technologies. A basic platform can be developed by applying GIS theory and functions for integrated planning of underground engineering to ensure the scientific exploitation of underground space. Furthermore, it assists in decision-making on the development and utilization of rock mechanics and rock engineering.

3.6 Development of 4D GIS technology

The temporal concern of GIS comes up as a topic since mechanical state and properties of rocks and structures change with time. For example, the profile of a tunnel lining tends to contract after construction. Therefore, the fourth dimension, i.e. time, is needed to make 3D GIS into 4D GIS, or known as TGIS. In the 4D GIS, tempo-spatial model of construction object, tempo-spatial database and tempo-spatial data index of original 3D geological model and object model are incorporated. The tempo-spatial properties are designed as a modeling system so that realtime tracking, calculation and analysis for substantial construction process can be realized. A 4D GIS should be able to answer users' queries of historical or current status, and predict the behavior of a geological unit or a structure in a certain period of time. Adding the fourth dimension looks simple but in fact is not the case since the geological condition changes with time. To consider the changes of data against time, a ground state modification data model is proposed, which can realize the updating of construction data [28]. The R* tree inquiry method is employed for efficient data query by partitioning temporal query path of index into space and time. Open issue to be addressed is the sudden occurrence of landslide, earthquake or accidents during construction, which can greatly change properties of geological bodies within a short period of time. The periodical geodetics network at domestic or global level provides dynamic information and can help to improve the situation. It is one of the future topics in developing the 4D GIS, making it beneficial to users in long-term or short-term decision-making.

4 Case studies

4.1 Digital management platform for Xiang'an subsea tunnel

The digital management platform for Xiang'an subsea tunnel in Xiamen, Fujian Province, Southeast China, is the outcome of a variety of digital technologies developed in rock engineering, including fundamental digital platform, system architecture, data organization and management method, modeling, visualization and realtime data management in tunnel construction.

The platform is based on a network comprising two parts, i.e. the server and the client, as shown in Fig.1. The server is used to create a database of tunnel lifecycle for data storage and management. On this basis, data services, model services, basic application services and professional application services are provided. Through a browser, the client cannot only

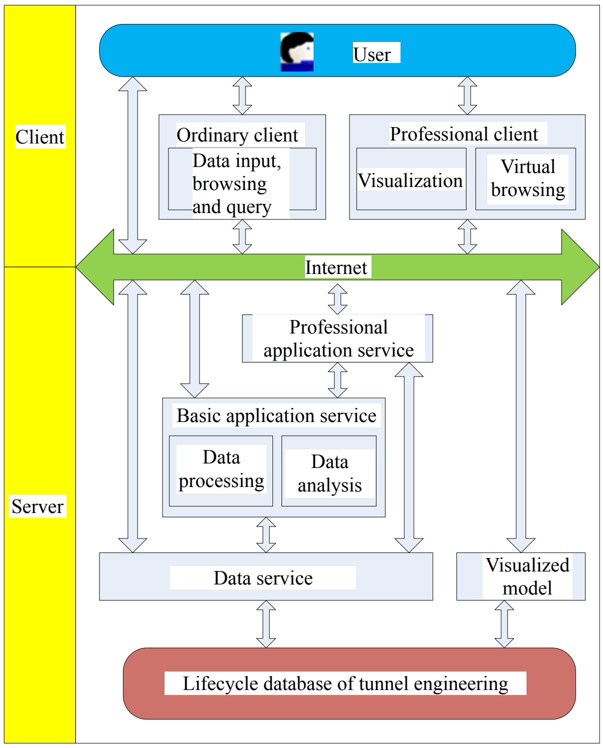
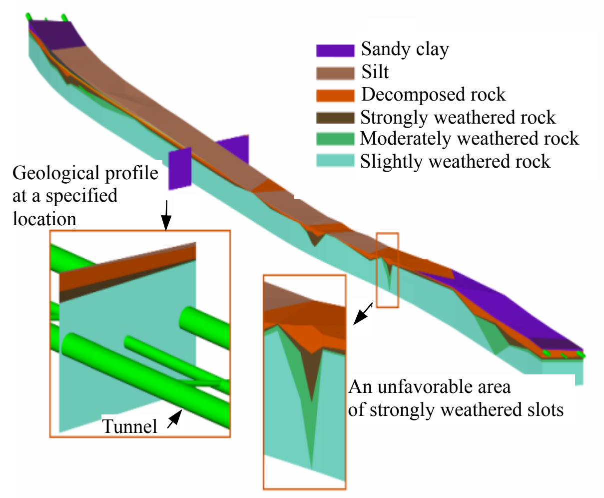


Fig.1 Framework of digital tunnel platform for Xiang'an tunnel.

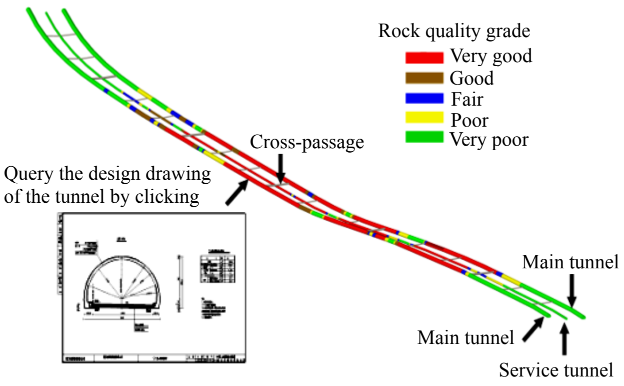
realize browsing, query and remote management of data, but also conduct 3D visualization, virtual browsing and computing and analysis of the project.

In the spatial data management system of the tunnel, data are described by project type tree and project structure tree. The attribute information is subdivided according to the characteristics of whole lifecycle and attached to the nodes on different levels of project structure tree for management.

The 3D geological modeling of Xiang'an subsea tunnel (see Fig.2(a)) adopts stratum modeling method based on generalized tri-prism (GTP). The method is completely based on borehole data and requires no manual intervention, which is ideal for processing layered geological body and describing complex geological structures like strata fold, pinch-out and crystal. The 3D model and surrounding structures of tunnel (Fig.2(b)) use automatic modeling approach. In automatic modeling, part models or cross-sectional models of the entire body are taken, e.g. tunnel structure and surrounding facilities are assembled or stretched according to axes positioning information and the certain organizational relationship. Finally, a complete model of the tunnel is generated automatically. It simplifies the modeling process of the tunnel and at the same time satisfies the needs for dynamic modeling. For example, the simulations of the tunnel construction



(a) 3D geological model and slice view.



(b) Cross-section query interface of the main tunnel, service tunnel and cross-passage.

Fig.2 3D geological model and main tunnel, service tunnel and cross-passage of Xiang'an tunnel.

process and the damages to tunnel structure in the real world can occur at any time.

In terms of the visualization of tunnel construction and inspection data, the TGIS technology was applied. The data structures in data model and temporal database can robustly reflect the dynamic process of tunnel construction.

4.2 Longtoushan tunnel: 3D geological model and management of construction data

Digital information platform of Longtoushan tunnel is a second phase development of ObjectArx based on 3D graphic platform of AutoCAD. The platform is implemented through the integrated use of object-oriented visual C++ and database technology. A dock box is designed for the platform containing six modules, i.e. general description, geological investigation, tunnel design, tunnel construction, tunnel monitoring, and tunnel operation and hazards prevention. The first four are the focus of the platform while the latter two serve as extendable interfaces for users.

(1) In the general situation module, an overview of Longtoushan tunnel project, including names of owner, constructor, monitoring organization and supervision unit, is displayed (see Fig.3).

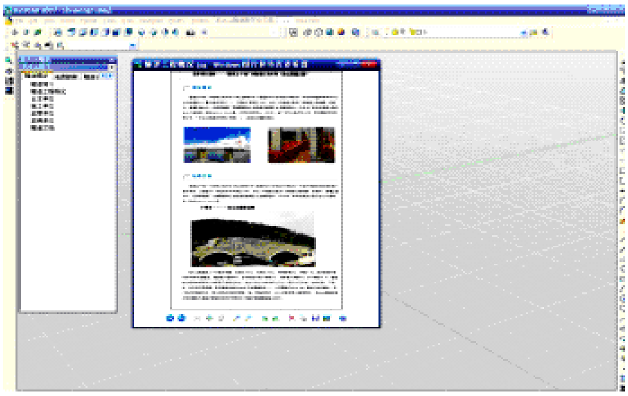


Fig.3 Description of the general situations of Longtoushan tunnel.

(2) Geological investigation module describes the geological survey method used in the project, transverse cross-section plan of survey, vertical section plan of left and right lines, geological floor plan and borehole data. The geological information is processed and digitized in the developed platform so that the slice view of the digital stratum information at any point of the tunnel can be instantly inquired and visualized, as shown in Fig.4.

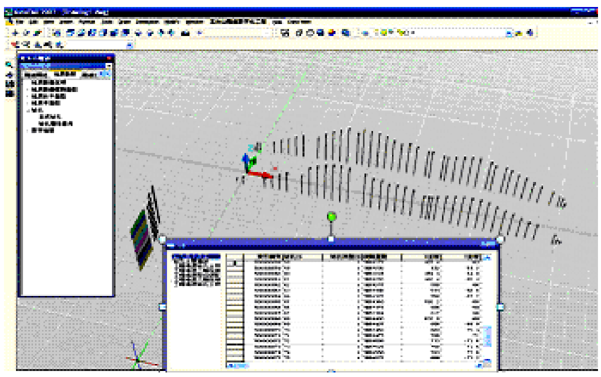


Fig.4 Query of borehole data of Longtoushan tunnel.

(3) Tunnel design module provides the information of drawings, modeling, query of tunnel properties and slicing, etc. The modeling method based on tunnel design axis can be used to automatically generate the tunnel entity and execute segment algorithm on the strata data of previous tunnel cases. Therefore, analysis model of Longtoushan tunnel can be easily built from the tunnel-related data or database files by inputting certain commands (Fig.5).

Figure 6 shows the query results of the tunnel

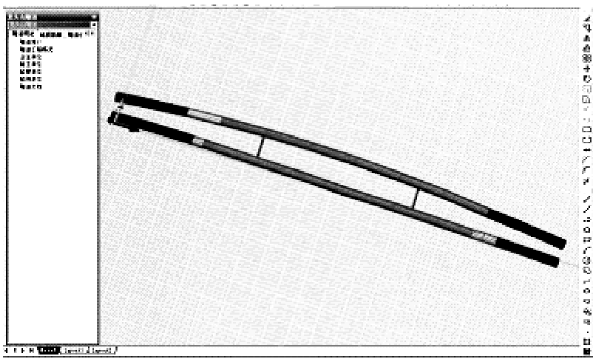


Fig.5 3D model of Longtoushan tunnel.

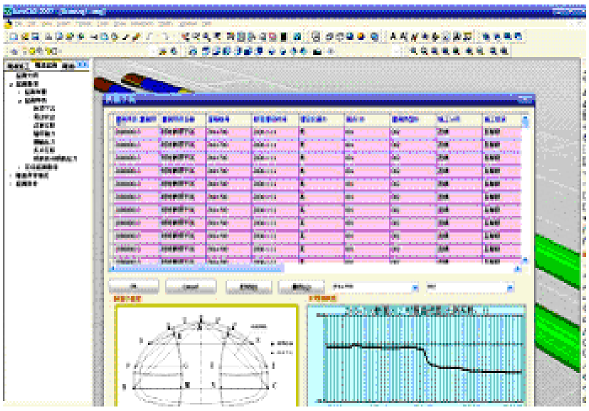


Fig.6 Query interface for displacement measured at controlling monitoring locations.

information. Users can access the information of the track of tunnel axes, drawings of transverse and vertical cross-sections as well as geological sketches and lithologic pictures of excavation faces.

(4) Tunnel construction module is composed of the description of tunneling steps, geological sketches and lithologic records of the excavation face, dynamic construction display and other functions. Figure 7 shows a good example of tunnel construction information.

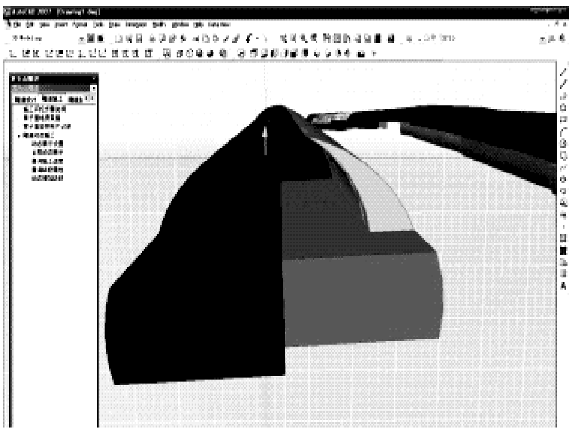


Fig.7 Visualization of surrounding rock excavation of Longtoushan tunnel.

(5) Tunnel monitoring module provides monitoring, visualization query, records of abnormal situations, and monitoring reports of the tunnel, as shown in Fig.6.

(6) Operation and maintenance module reserves interfaces for operation and maintenance information, making it possible to record and manage the monitoring information related to ventilation, illumination, fire fighting, traffic, etc. during operation and management, as well as the maintenance information from daily, regular and detailed checking.

4.3 Wangfenggang coal mine: 3D design and analysis powered by digitization

Combined with 3D model and mine database, a realtime mine information system based on 3D digital strata is developed, providing an authentic, reliable, practical and highly efficient platform for shaft design and production management of Wangfenggang coal mine, as shown in Figs.8–10. The platform is composed of five modules, including module of coal seam and fault, module of laneway aided design and analysis, module of general ground surface situation and working condition, module of auxiliary view and layer managements, and module of dynamic visualization (an independent system).

(1) For management and maintenance purpose of the

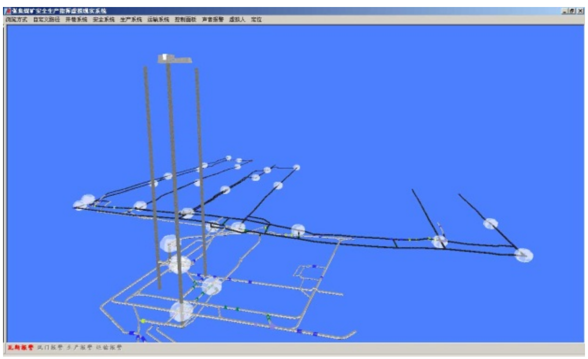


Fig.8 Digitization of laneways of Wangfenggang coal mine.

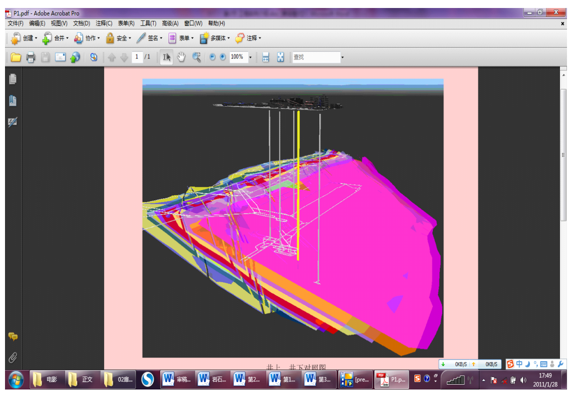


Fig.9 3D visualization of surface and underground models of a shaft.

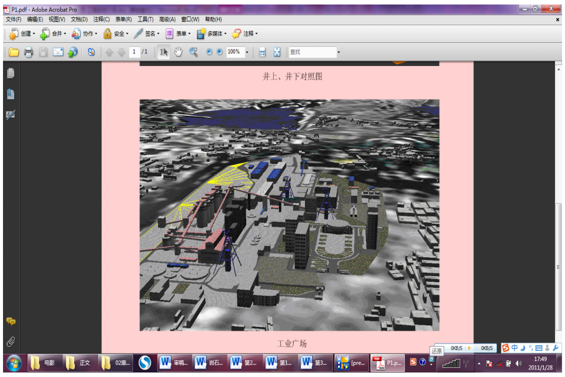


Fig.10 Simulations of industrial square of Wangfenggang coal mine.

coal mine, geological data (e.g. comprehensive column of strata, borehole column, geological section map), coal seam data (e.g. contour map of coal seam), laneway data (e.g. layout of laneway, section of laneway) and ground surface data (e.g. geological and topographic maps) are collected and organized. The database for the above described data is developed, which helps to reduce the cost of paper drawings and manpower for filing. Users can conveniently manage and maintain a variety of data related to coal mine using the database.

(2) In the modeling of coal seam, the 3D mine seam model was built based on cross-sectional data from investigation, using GTP volume element mapping and reference TIN models. Part of digital strata can be updated according to the spatial variations in coal seam and floor. By this modeling method, the strata structure and the deposition law can be demonstrated vividly and directly, enhancing the spatial concept of the coal distribution. It provides a good guidance for exploration and utilization of underground resources as well as implement and construction of project.

(3) In the modeling of laneway, 3D modeling technology based on CSG (the loft method of laneway inside and outside wall) is employed. The parametric and interactive design process is formulated and realtime query function is implemented. Through the laneway modeling, the spatial relationship of laneway is accurately represented in 3D environment. Users will find it easy to understand the complicated geological information and laneways distribution. The parametric and interactive design process of aided laneway could also assist engineers in arranging the engineering work more quickly and accurately in 3D space. The idea of modeling based on the digitization platform is generally applicable to other rock engineering projects. For example, it has been applied to the design and modeling of a nuclear waste disposal site shown in Fig.11.

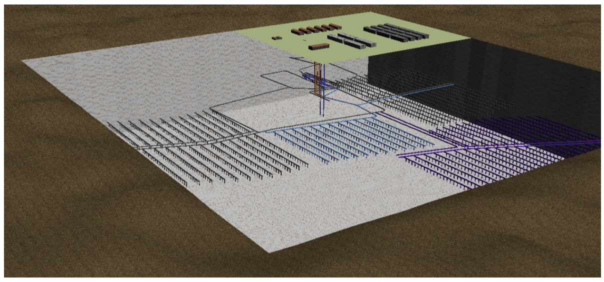


Fig.11 Virtual reality aided design of a nuclear waste disposal site.

(4) Algorithms for spatial analysis between laneway and coal seam and those for laneways are developed. Coupled with database, interactive user interface, 3D modeling function and simple spatial analysis function, these algorithms help to optimize the design and construction of laneway, promote the construction efficiency, and decrease the engineering risks.

(5) In the realtime information system, some auxiliary tools such as dynamic 3D meshing, dynamic 3D compass and realtime 3D scaling, and color legends of the coal seam and laneway are added for users. AutoCAD performs well in graphic element computation and accurate geometrical representation. However, it is not an ideal platform for 3D visualization. These auxiliary tools can help users to get clear information about the geological spatial structure and laneway distribution in the mine model.

(6) In 3D visualization, the efficient 3D rendering models of ground surface, coal seam and laneway are constructed. Animation for three mining production systems (transportation, ventilation and coal production) is developed, recording a 5-minute 3D promotion video of the mine. 3D visualization technology makes the complicated mine system easy to be understood and visualized. It also enhances the communications and connections between the mine and the external world. Wangfenggang mine as a test mine is a good example. On the other hand, by 3D visualization extensive interface, the modules of design and management can be integrated on the display platform of the mine so as to realize the integration of design, management and visualization.

The realtime information system based on 3D digital strata of Wangfenggang coal mine holds the following functions, i.e. modeling and updating of digital mine stratum, aided design and analysis of laneway, realtime query of laneway data and dynamic visualization, and browsing and display. The system is featured by realtime processing, visualization, reliability, economic integrity and extensibility, which is a breakthrough to the traditional 2D graphic design and management method. The efficiency of coal mine production and management is improved. The developed digital platform is expected to be widely applied to large coal mine enterprises.

4.4 Digitization of indoor rock uniaxial compressive test (UCT)

As a preliminary trial of digitization of rock mechanical data, a data structure for digitization of rock UCT is developed, as shown in Fig.12. The architecture of data is designed by considering the link between the type of test data and test objects. Rock mechanical test data are sorted and encoded referring to the standards in DIGGS. Then a standard description format for rock test data is proposed using XML, and denoted as UML, where "U" is the short for UCT. Finally, a catalog service web (CSW) platform is designed and developed based on the concept of web service, as shown in Fig.13.

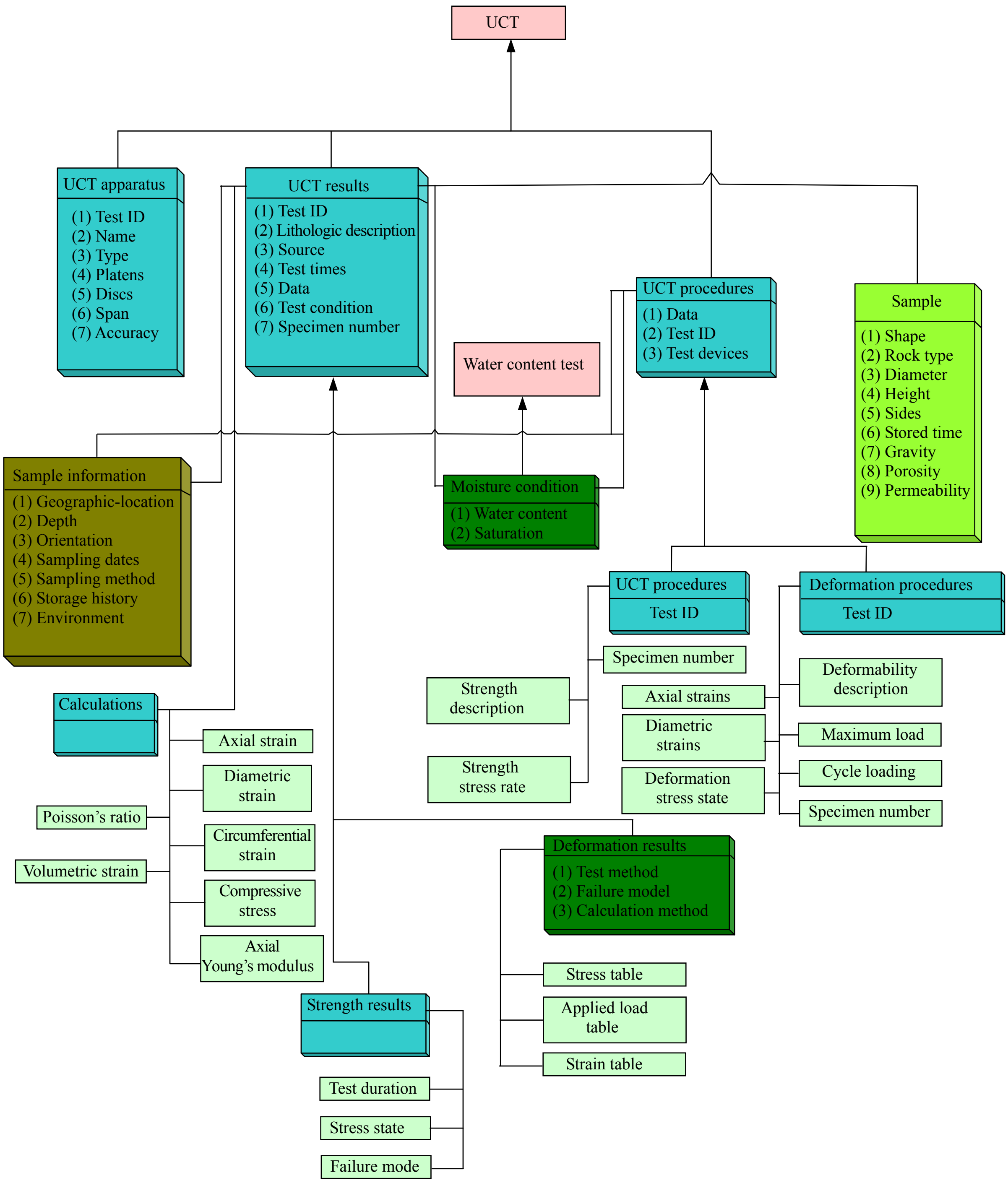


Fig.12 UML data architecture of rock UCT.

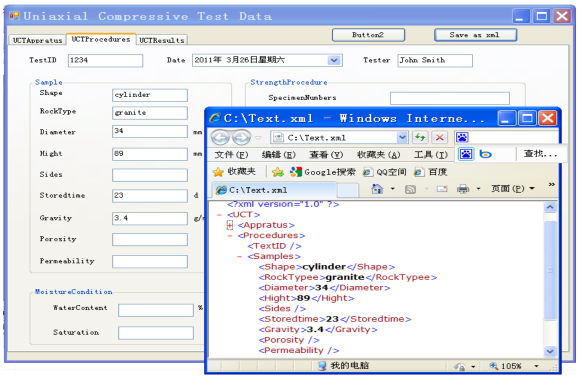


Fig.13 Web based UML interface for compression test.

5 Conclusions

Digitization in rock mechanics and rock engineering has propelled the transfer, development and application of new digital technologies in this field. As shown in the case studies, digitization has already presented its significant and value in engineering construction and management. However, two technical and management issues remain to be addressed. The first is the standardization of data format and test method, which is mostly concerned not only in research on rock mechanics but also in substantial rock engineering projects. Great efforts have been devoted from international societies for rock mechanics and geotechnical engineering to solve this problem. However, the complexity, uncertainty and case-specific properties of rock engineering bring difficulty in establishing an efficient and generally acceptable system of standards. The second issue is how to implement digitization throughout various stages of a project from planning, investigation, data collection during construction, realtime modeling and analyzing, remote monitoring to decision-making. Implementing digitization and connection through various stages is beyond the scope of technical issues.

In future development, it is essential to create a good network integration environment to offer a system providing value-added service. Existing technologies and potential ones need to be utilized to expand the technical connotation of digitization system.

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