# Discussion on a methodology for the digital reconstruction of complex fault structures in coal mines

**Hongwei Wang** (whw@cumtb.edu.cn)
China University of Mining and Technology, Beijing https://orcid.org/0000-0002-9339-7013
**Zeliang Wang**
China University of Mining and Technology, Beijing
**Yaodong Jiang**
China University of Mining and Technology, Beijing
**Jiaqi Song**
China University of Mining and Technology, Beijing

**Research**

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# Abstract

The visualization of complex geological structures can provide technical support for accurate prediction and prevention of coal mine disasters. Taking fault structure as an example, this study proposes a new digital reconstruction method to realize the visualization of geological structure. The methodology for the digital reconstruction of complex fault structures is composed by the following four aspects, including collection and fidelity of multi-physical field data of fault structure, transmission of multi-physical field data, multi-physical data normalization and digital model of fault structures. The key scientific issues of this methodology to be resolved includes in-situ fidelity of multi-field data and normalized programming of multi-source data. In addition, based on the geological conditions in Da 'anshan coal mine in the mining area of western Beijing, China, this paper makes a preliminary attempt to establish a digital model of fault and fold structures by this methodology.


# 1 Introduction

Due to the continuous increase of the depth and intensity of coal mining, coal bursts have become one of the major dynamic disasters in the underground coal mining around the world (Jiang et al. 2014; Yuan et al. 2018; Wang et al. 2021). There are many inducements for coal bursts accidents, among which complex geological structure (mainly refers to faults, folds and phase transitions) is one of the main factors that have been studied. According to statistics, coal bursts occurs near the geological structure accounts for more than 70% of the occurrence times of all coal burst accidents (Pan et al. 2003). For example, on August 2, 2019, coal bursts occurred under the influence of a fault in the roadway in Tangshan coal mine in Hebei province, China. On February 22, 2020, another coal burst accident occurred around an unstable thrust fault during the coal seam mining in Longgu coal mine in Shandong province, China (Wang et al. 2017; Qi et al. 2019).

Numerous investigations have been carried out to study the mechanism of fault structure formation, the criterion of fault activation and the visualization of fault structure. Chen et al. (2020) studied the development process of reverse faults and the evolution of stress and deformation of the hanging wall using the developed geological experimental system. The results show that the dip angle of reverse faults mainly depends on the property of the rock, and the drop mainly depends on the horizontal stress. Qi et al. (2019) adopted the means of field measurement analysis, theoretical analysis and numerical simulation to study the stress distribution of overlying rock structure and the occurrence mechanism of coal bursts during the mining process of mining face under the condition of large fault. Zhang et al. (2020) studied the unloading effect of thrust fault caused by mining disturbance by means of similar simulation and numerical simulation, and clarified the mode and process of unloading instability of thrust fault in Yima mining area. Wang et al. (2019) took the evolution characteristics of stress field on fault slip surface as the research object and studied the precursor information of fault slip and instability when mining disturbance occurred on mining face through similar simulation and numerical simulation. Yuan et al. (2015) introduced the visualization method of fault structure based on 3D volume rendering technology. Zhang et al. (2009) proposed a modeling method of complex geological faults in geotechnical engineering based on element reconstruction.

However, the traditional research methods cannot accurately obtain the stress distribution on the fault surface. The unclear understanding of geological conditions and the unknown evolution process of multiple physical fields are the main limitation for the accurate prediction of coal bursts. In recent years, with the rapid development of information and communication technology, traditional industries are accelerating the industrial digital transformation. Digitization refers to using information system, various sensors, machine vision and communication technologies to introduce the complex and changeable information in the physical world into the computer to form the identifiable, storable and computable data, and then use these data for unified processing, analysis, visualization and application (Belk et al. 2003; Yoo et al. 2010). The digital method provides a new idea for the reconstruction and visualization of multi-physical fields of complex fault structures, and the digital twin technology based on the digital idea is a new generation of information technology and covers the whole cycle, whole process and all elements of the project, playing the role of bridge and link between the physical world and the information world. It includes three modules: physical model, virtual model, data interface and information mutual feed interface between physical entity and digital model (Li et al. 2014; Tao et al. 2018), the conceptual diagram is shown in Fig. 1. Digital Twin presents real-time dynamic visual models to users based on data drive, enables users to have a profound and detailed understanding of the current health state of the system, and assists users to make decisions through data analysis, simulation iteration and other means.

Figure 1 **Conceptual diagram of digital twin system**

Digital twin is a widely used technology and system in aerospace, advanced manufacturing, engineering and construction. Airbus uses digital twin in its aircraft assembly process to increase automation and reduce lead times. Siemens built a system model of the production process based on the idea of digital twin, and realized the product design and the virtualization and digitization of the manufacturing process by analyzing all the links of the production process through simulation. The American company ANSYS, which is famous for finite element simulation, has proposed a digital twin simulation scheme based on finite element simulation and system-level simulation as the ultimate goal (Tao et al. 2019). At present, digital twin technology is seldom used in engineering construction, mainly concentrated in underground space engineering, bridge engineering and water conservancy engineering. Shim et al. (2019) developed a three-dimensional digital twin model for the maintenance of prestressed concrete bridges based on three-dimensional information management and digital image inspection system. Kaewunruen et al. (2019) and Lian designed a full life cycle sustainable digital twin system for urban underground rails. Lu et al. (2019) used digital twin technology to solve the problem that the existing digital model of reinforced concrete bridge could not restore the bridge state ideally.

Digital twin is a simulation process that integrates multi-physical fields, multi-scales and multi-probabilities. Its significant feature is the processing of massive data. How to realize the fidelity of the data-driven model and the fusion of multi-source data is the key to model reconstruction, Numerous investigations have been carried out to study on these. Aiming at the problem of data acquisition and fidelity: Zakerzade et al. (2018) uses Kalman filter to process the numerical noise input by the sensor to improve the accuracy of the estimation results. Zhang et al. (2021) studied the data acquisition method of machining process of CNC machine tools and established the spatio-temporal mapping model corresponding to machining process data and parts processing position. Li et al. (2021) proposed a parallel configurable acquisition method of multi-source heterogeneous data based on field programmable gate array (FPGA) to ensure real-time data acquisition. Tao et al. (2018) points out that the fidelity of digital twin model is constrained by geometry, physics and behavior rules. Aiming at the problem of multi-source data fusion: Guo et al. (2018) proposed a multi-data source information fusion fault diagnosis method based on improved D-S evidence theory. Wang et al. (2020) et al. Proposed a dynamic data-driven modeling and simulation method for digital twins. The physical entities and sensors in CPS were modeled by random finite sets, and supported the data-driven simulation model operation by the prediction and correction process based on Bayesian inference. Ge et al. (2020) proposed the Digital Thread method to manage the information flow of the Digital twin mining face system. The data of the information flow was divided into periodic data, random data and sudden data for modeling processing, so as to ensure the data-driven and stable operation of the Digital twin mining face.

In conclusion, digital twinning technology has been widely used in aerospace, advanced manufacturing and other aspects, and scholars have achieved fruitful scientific research achievements. However, the application of digital twin in mining engineering is still in the initial stage, most of the simulation objects are aimed at small-scale physical models, which have not yet to achieve accurate reconstruction of large-scale multi-physical field models in the space of complex geological structures. Although some achievements have been made in multi-source data fusion, it is difficult to collect and transmit data due to the particularity of fault geological conditions. Therefore, this paper proposes a digital twin-based method and architecture of complex fault structure coal mine digitization, aiming to provide some ideas and ideas for realizing the digitization and information modeling of complex geological structure in the future. The digital reconstruction is not a simple construction of faults geometry, but a comprehensive reproduction of multi-physical field data of fault structure. The digital reconstruction scheme is expected to have the following four steps.

## 2 Digital Reconstruction Scheme Of Fault Structures

# 2.1 Collection and fidelity of multi-physical field data of fault structure

Multi-physical field data of fault structure include fault structure geometry, composition of overburden rock masses, in-situ stress distribution and boundary conditions. It should be noted that the fidelity of in-situ stress and boundary conditions is of significance in the digital reconstruction of fault structures (Wang et al. 2020). In this study, considering the high cost of data collection, large scale of the fault structures in underground coal mine and the uncertainty of complex geological conditions, a physical model with fault structure under laboratory environment is initially constructed. Figure 2. presents the schematic diagram of multi- field data collection and fidelity under laboratory environment.

Figure 2 **Schematic diagram of multi-physical field data collection and fidelity**

The collection of multi-physical field data is mainly based on the geophysical monitoring methods, including seismic high power geological radar, wave advanced detection, transient electromagnetic detection and borehole stress relief method for in-situ stress. High power geological radar can detect and obtain the location coordinate, fault throw and dip angle of complex fault structures from the ground surface to underground roadway or mining face. These geometrical parameters are the main data for the geometric morphology fidelity of fault structures under the laboratory conditions. The wave advanced detection is employed to obtain the composition of overburden rock masses and further provide the data for the fidelity of rock strata distribution. Transient electromagnetic detection is used to confirm the hydrological environment near the faults area and determine whether to implement water fidelity within the physical model of the fault structures. Borehole stress relief method is a main method to detect in-situ stress around the fault structures.

In this study, based on the borehole stress relief method, a new dynamic stress monitoring system will be developed. This system can monitor not only in-situ stress, but also mining-induced stress and tectonic stress. This system is composed of borehole stress sensors, data terminal integrator, data analysis software and image figure out software, as shown in Fig. 3. According to the detection data form the dynamic stress monitoring system, the boundary conditions of fault physical model can be established in the laboratory. By developing an adaptive boundary pressure propulsion device, establishing a data interface with the stress monitoring system, and autonomously applying a stress boundary condition similar to the in-situ stress of the coal roadway, the fidelity of the stress boundary condition is realized.

Figure 3 **Dynamic stress monitoring system**

Based on the deep engineering failure simulation system, the overburden rock mining-induced stress monitoring system, the fault tectonic stress monitoring system, the overburden rock displacement monitoring system, the dynamic scanning system of the ground penetrating radar for the internal structure of the overburden rock, and the full-information acoustic emission signal analysis system are connected. The system is used to collect overlying rock mining stress field, overlying rock movement displacement field and fault sliding stress field data. It is worth mentioning that when the size of the similar model is determined, the more sensors are installed, the more accurate the monitoring results will be. However, a large number of embedded sensors will cause stress concentration in the physical model, which will affect the experimental results. Therefore, the sensor layout needs to be determined according to the test situations.

# 2.2 Transmission of multi-physical field data

The collection of multi-physical field data poses a challenge to the massive data transmission in the physical model. Ensuring the efficient transmission of massive data is a key step to realize the digital reconstruction of complex fault structures. To efficiently transmit the multi-physical field data from physical model to digital model, the following two modules should be paid more attention. The first one is the data interface module for real-time data interaction while another one is a parallel algorithms module for data sharing, fusion, and integration. Figure 4 presents the process of multi-physical field data transmission.

Figure 4 **Multi-physical field data transmission**

Due to the different types of collection equipment, multiple information transmission connections are formed. How to ensure the efficient summary of information flow is the basis of digital reconstruction of fault structure.

The first module is to establish the data interface for dynamic real-time interaction of multi-physical field data for a physical model to the database. Based on high speed, high stability and low delay data transfer protocol, extracting the real-time dynamic data of multi-physical field sensors include geometric shape, displacement field and stress field from physical model in a unified way. The second module is to develop high-performance parallel algorithm of data dynamic sharing, fusion and integration is compiled to undertake the information transmission from physical model to digital space. The algorithm can automatically identify data types, automatically coordinate the allocation of resource nodes, reduce data redundancy, and ensure the high efficiency and timeliness of data transmission.

## 2.3 Multi-physical data normalization

The normalization of multi-physical field data mainly refers to the generalization, organization, coding and storage of stress, strain, and acoustic emission data, and the process is shown in Fig. 5.

Figure 5 **Schematic diagram of multi-physical data normalization**

The data generalization is to preprocess the data, realize the rapid extraction of data features, and convert the original data of different formats into the unified format; The data organization is to assign coordinate information to data from different sources to form the standardization of spatial-temporal information, check data quality and filter data that do not meet requirements; The data coding is to catalog the processed data, design the logical structure according to the attributes and characteristics of the data, correlate each data with serial numbers, and pack the file data into blocks after encoding to prepare for data storage; The data storage is to integrate the processed data into the database and which can be managed, transmitted and extracted uniformly. Finally, through the above four steps, the data structure database of stope history and operation state in full time domain, full factor and whole process is established.

## 2.4 Digital model establishment of fault structures

Based on the collection, transmission and normalization of the multi-physical field data, the digital reconstruction of fault structure is the digitalization of multi-physical dynamic data, rather than the traditional numerical modeling. The digital model of fault structure includes the fault images, stress data, displacement data, drilling data, energy data and so on. Through the modular integration platform, multi-physical field data are correlated, fused, rendered and presented in an integrated way, which can provide people with a complete observation perspective in time and space. Aiming at the complex structure location that is difficult to observe in the physical system, the problem can be solved through multi-source data interpolation and inverse fitting, thereby the system can support the in-depth observation of the operating state of the system. The system can also track the real-time data, historical data and operating status of the physical model to form a low-latency, high-fidelity mirror relationship. The digital reconstruction process of fault structure can be divided into the following three steps, as is shown in Fig. 6.

Step1: Based on the fault structure parameters and borehole data extracted from the database, the original data or discrete data interpolation and fitting method is derived to reconstruct the three-dimensional visual static geological model.

Step2: Based on the collected multi-physical field data, the two-dimensional and three-dimensional interpolation fitting algorithm of complex geophysical field is studied to restore the unmonitored multi-physical field distribution.

Step3: According to the coordinate and time information, the interpolated multi-physical field data is synchronously restored to the static geological model, and the 3D cloud map is automatically generated to realize the visualization of multi-physical field in the mining process of the mining face.

Figure 6 **Digital reconstruction of fault structure**

The fault structure model can not only generate dynamic three-dimensional cloud images, but also have the functions of zooming, rotating, cutting at any position and data extraction, which is convenient for users to observe the target object in depth.

## 3 The Key Scientific Issues To Be Resolved

# 3.1 Fidelity of multi-physical field data

Considering the complex geological conditions, a physical model of the fault structure is explored and constructed under laboratory conditions. The fidelity of multi-physical field data mainly includes fault structure geometry, composition of overburden rock masses, in-situ stress distribution and boundary conditions. Therefore, high-sensitivity and high-precision sensors, adaptive boundary pressure propulsion device and multi-scale simulation test platform are developed in this study. The high-precision sensors can monitor the in-situ stress data in real time, and the adaptive boundary pressure propulsion device can realize the adaptive pressure on the boundary of the model according to the collected stress data. The structure of platform is shown in Fig. 7.

Figure 7 **The structure of multi-scale simulation test platform**

The experimental platform is composed of a base, left and right plates and an upper roof. The side plates and the roof are installed with multiple evenly distributed pressure heads, which can realize the seamless loading of the model under the control of computer and servo hydraulic control system. The right and the upper plates can slide freely, which enables multi-scale modeling. At the same time, a new dynamic stress transmission algorithm is developed to automatically identify, filter the error data and convert the boundary loads, which can realize the transmission and fidelity of the boundary stress data.

## 3.2 Normalized programming of multi-source data

Digital reconstruction of fault structure requires effective fusion of multi-physical field data. However, due to differences of data collection sensors, time scale and error accuracy, the normalization of multi-physical filed data is the basement of data transmission and centralized presentation. Therefore, it is of significance to study the normalization programming algorithm of multi-source heterogeneous data. The major idea of the algorithm is mainly embodied in four steps including generalization, organization, coding and storage. The detailed process is shown in Fig. 8.

Figure 8 **Normalized programming of multi-source data**

Based on parallel algorithm, a normalized algorithm is developed to extract characteristic parameters of multi-source data, filter redundant data and distribute coordinate information of monitoring points automatically. According to the data relationship, the data logical structure is designed. Finally, the multi-source data normalized structure database is established. The normalized data can be managed, transmitted, extracted uniformly through the database, which provides a data basis for later digital reconstruction.

# 4 Preliminary Attempt On Digitalization Of Fault Structure

## 4.1 Geological conditions of the Da'anshan coal mine

According to the geological background of Da 'anshan coal mine in the mining area of western Beijing, China, this paper shows a preliminary attempt results of digital reconstruction. The following tectonic description is based on the previous geological survey studies (Wang et al. 2017). The Da’anshan coal mine is located in Fangshan District in Beijing and has a length of 9 km in the strike direction and a width of 2 to 4 km in the dip direction. The Da’anshan coal mine is excavated in the south limb of the Miaoanling-Tiaojishan syncline with the Jiulongshan syncline to the east, the Fuping anticline to the south, and the Baihuashan syncline in the west, as shown in Fig. 9.

Figure 9 **Schematic map of geological structures in the mining area of western Beijing**

Due to compressive stress, large amounts of compound folds are present within the Da’anshan coal mine; these structures are regarded as the primary tectonic features of the mine. The primary fold structures are the Dahanling overturned anticline, which has dip angles ranging from 10° to 90°, and the Dahanling syncline, which has dip angles ranging from 50° to 90°, as shown in Fig. 10. Subsidiary fold structures are well developed in the axis and both limbs of the primary fold, and these smaller folds are accompanied with a large number of fractures in both the strike and dip directions. There are many thrust faults in Da'anshan coal mine that mainly result from horizontal compressive stress; these faults have a maximum drop height of 150 m and a maximum dip angle of 77°.

Figure 10 **Tectonic section of the Da'anshan coal mine**

## 4.2 Establishment on the digital model of geological structures

Based on the geological data such as borehole, geological section and contour line collected in-site, the applicability of various interpolation algorithms in the mining area is compared and analyzed. Finally, the Kriging algorithm is selected as the optimal method due to its smallest error.

The interpolation method was used to encrypting the data elevation of different layers, and the data were imported into Midas to build DEM surfaces of the ground and strata. Based on the geological profile and geological topographic map, the main geological parameters of the fault, such as spatial position, length, drop, dip Angle, and fault plane were extracted. Finally, according to the generated DEM plane, fault plane and boundary constraint, the block model is cut to build a three-dimensional visual static geological model of fault structure.

Through the normalization processing of the collected multi-physical field data, a structured database is established in the database software SQL. Based on the Lagrange and Shepard interpolation methods, the three-dimensional interpolation fitting processing of the data was realized, and the stress and displacement data after encryption were restored to the corresponding positions of the model according to the coordinates. By assigning attributes to the mesh, horizontal and vertical stress and displacement contours are obtained to realize the visualization of fault structure geometry and multi-physical fields, as shown in Fig. 11.

Figure 11 **Digital reconstruction effect of Da'anshan coal mine**

# 5 Conclusions And Prospects

(1) The first key scientific issue for digital reconstruction of fault structure is to conduct fidelity of the collected multi-physical field data. The seismic high power geological radar, wave advanced detection, transient electromagnetic detection and borehole stress relief method for in-situ stress are employed to collect multi-physical field data around the fault structure. A new dynamic stress monitoring system accompanied by an adaptive boundary pressure propulsion device is used to apply the fidelity stress boundary conditions.

(2) The second key scientific issue for digital reconstruction of fault structure is to realize normalized programming of multi-source data. Based on parallel algorithm, this paper develops normalized algorithm to extract characteristic parameters of multi-source data, and filters redundant data and to

distribute coordinate information of monitoring points automatically. According to the data relationship, this paper designs the data logical structure and establish the multi-source data normalized structure database, which provides a data basis for later digital reconstruction.

(3) According to the geological conditions in Da 'anshan coal mine in the mining area of western Beijing, China, a full-scale, 3D visual digital model which can restore the fault geological structure and the stress and displacement distribution is established. It needs to be improved that this paper only carried out the work in the establishment of digital fault model and representation of the stress and displacement distribution in static. The related data transmission and programming to realize dynamic data visualization need to be further studied.

## Declarations

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# Figures

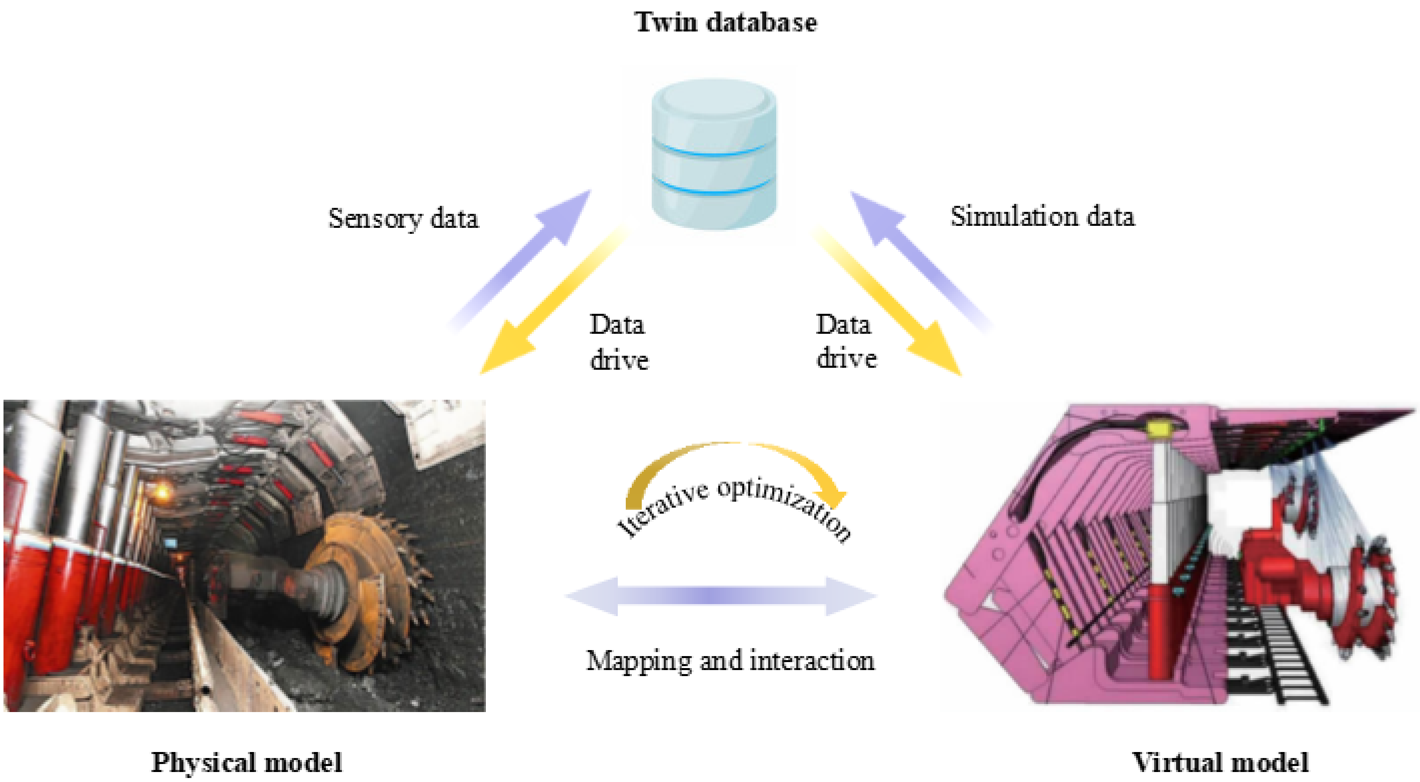
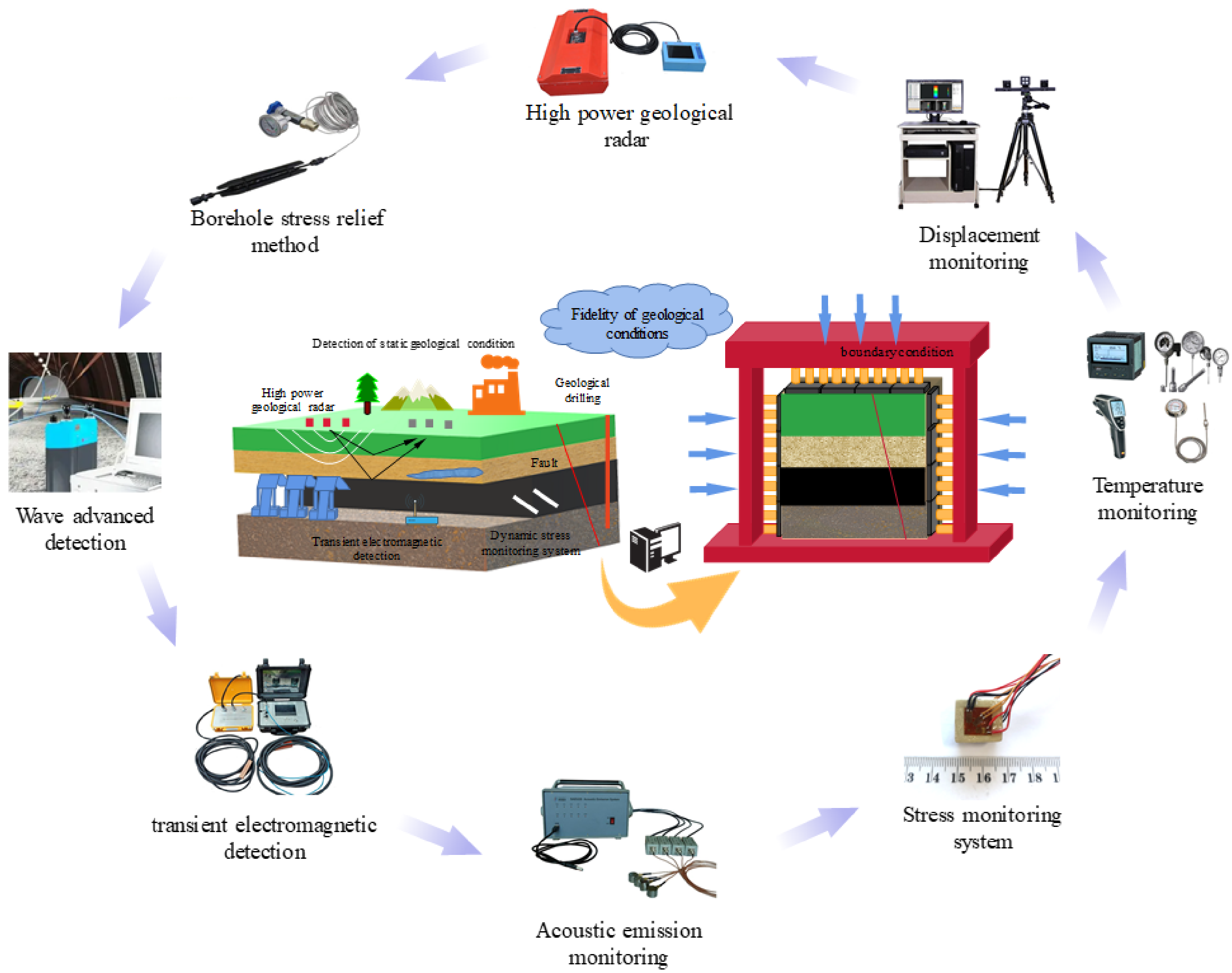


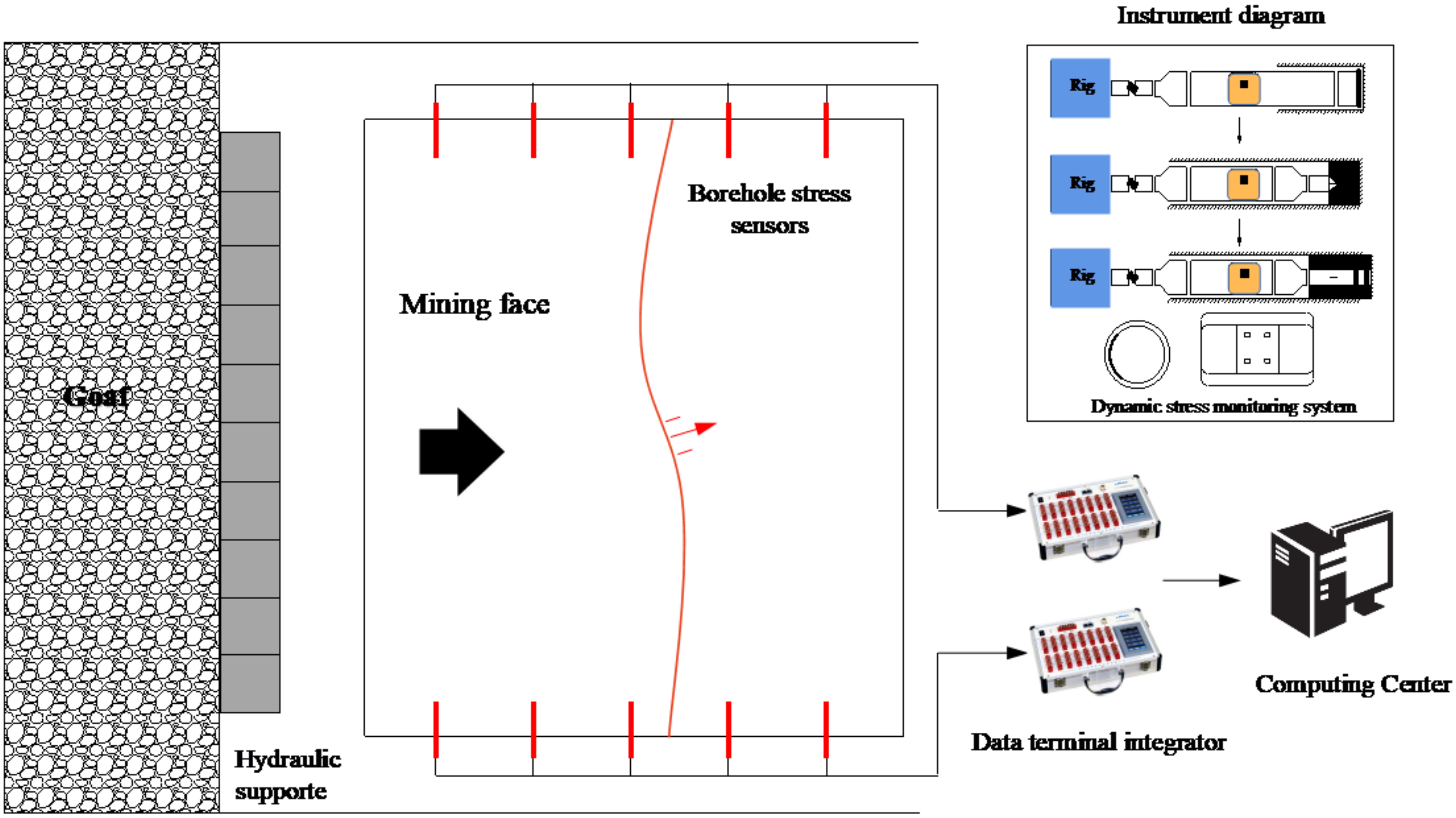

**Figure 1**

Conceptual diagram of digital twin system




## Figure 2

Schematic diagram of multi-physical field data collection and fidelity




## Figure 3

Dynamic stress monitoring system

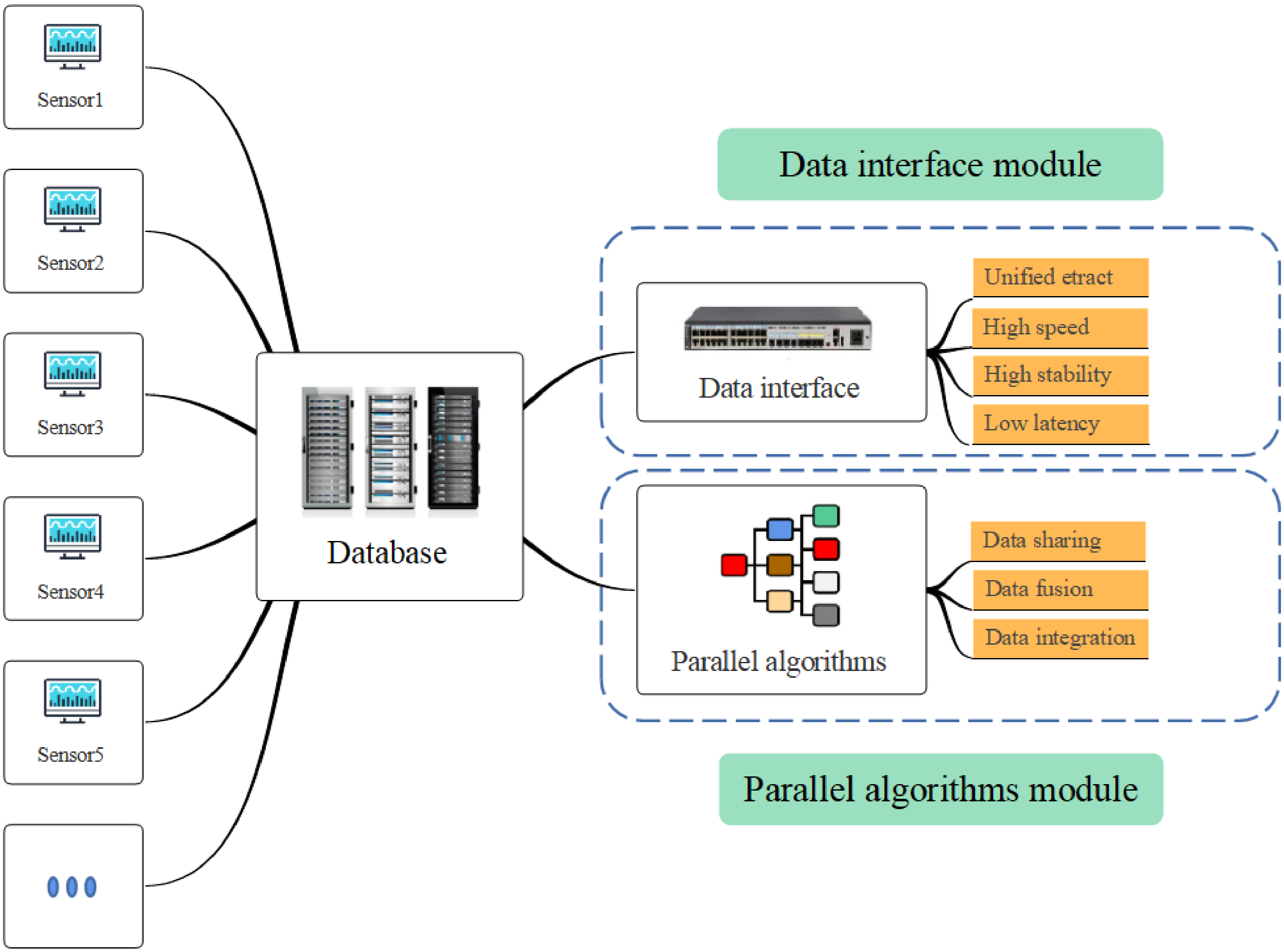
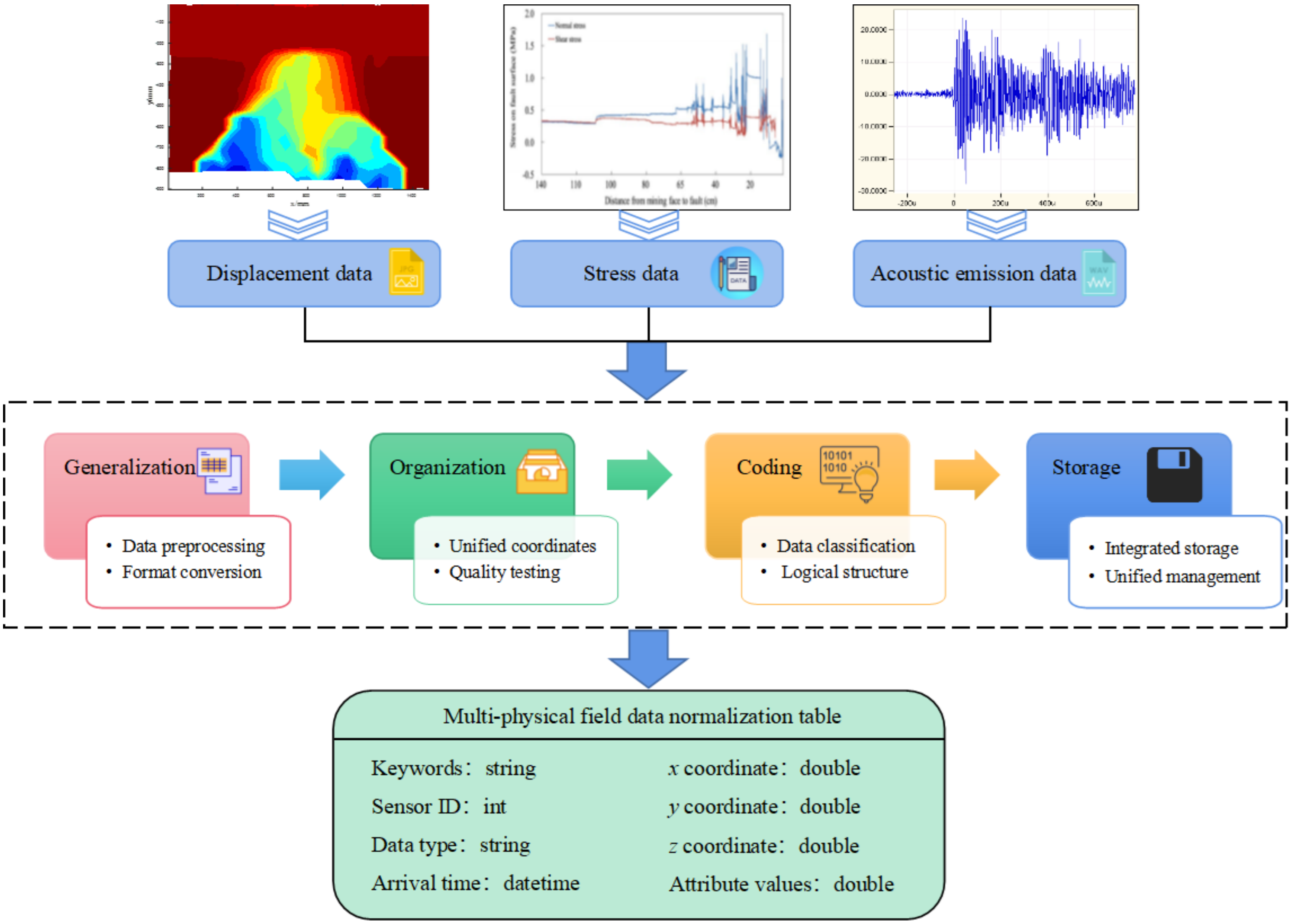


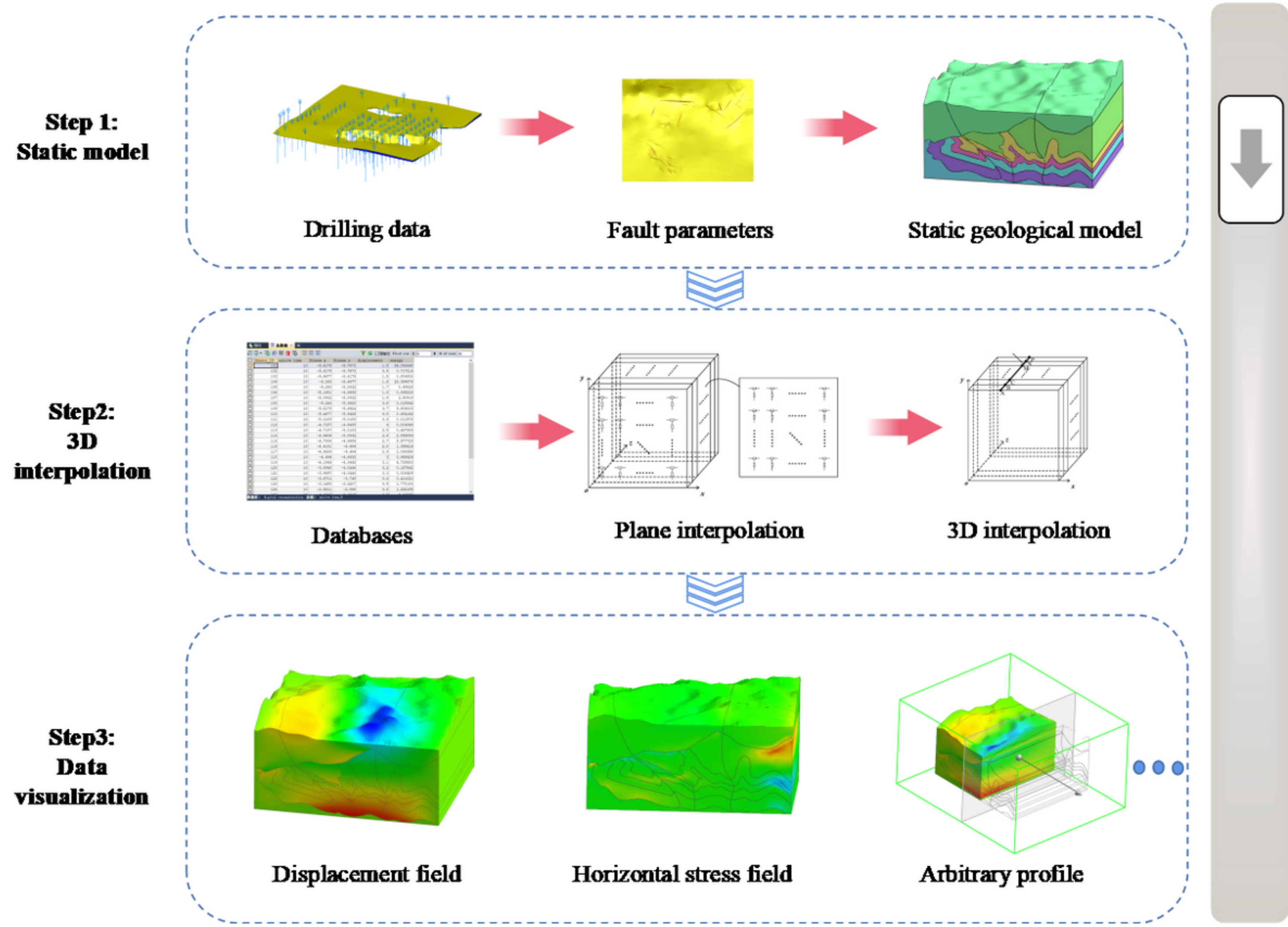

**Figure 4**

Multi-physical field data transmission



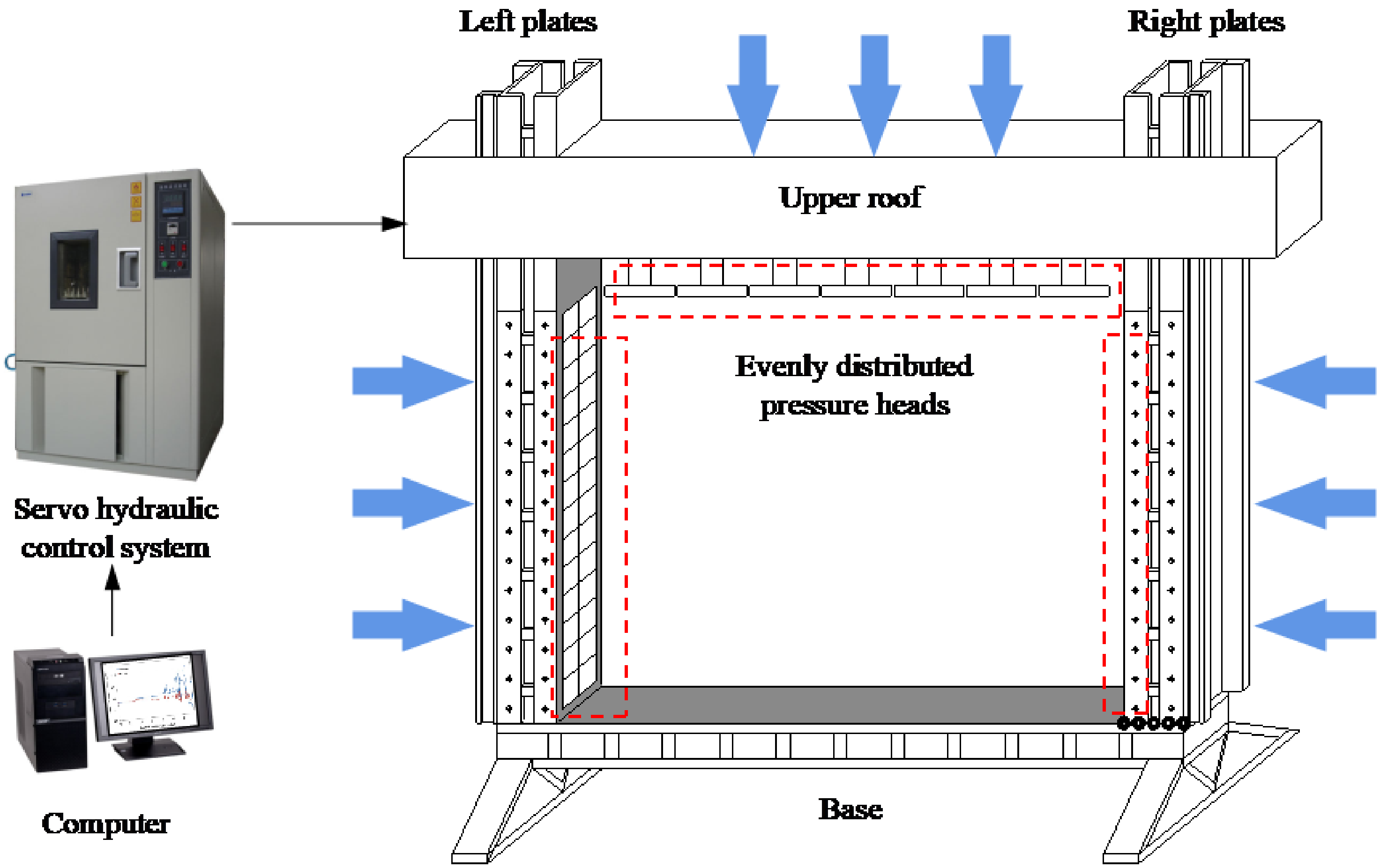

## Figure 5

Schematic diagram of multi-physical data normalization




## Figure 6

Digital reconstruction of fault structure




## Figure 7

The structure of multi-scale simulation test platform

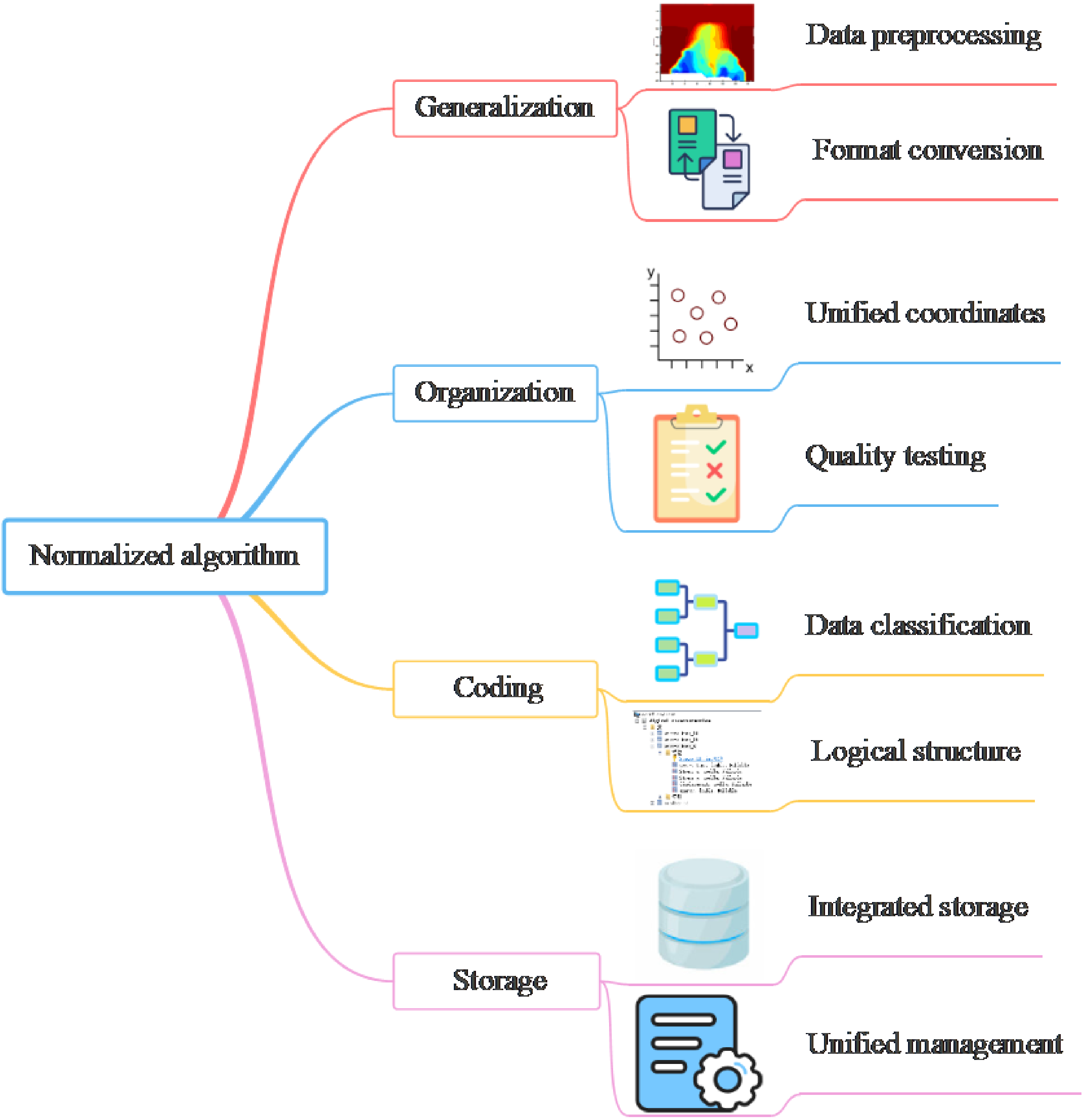
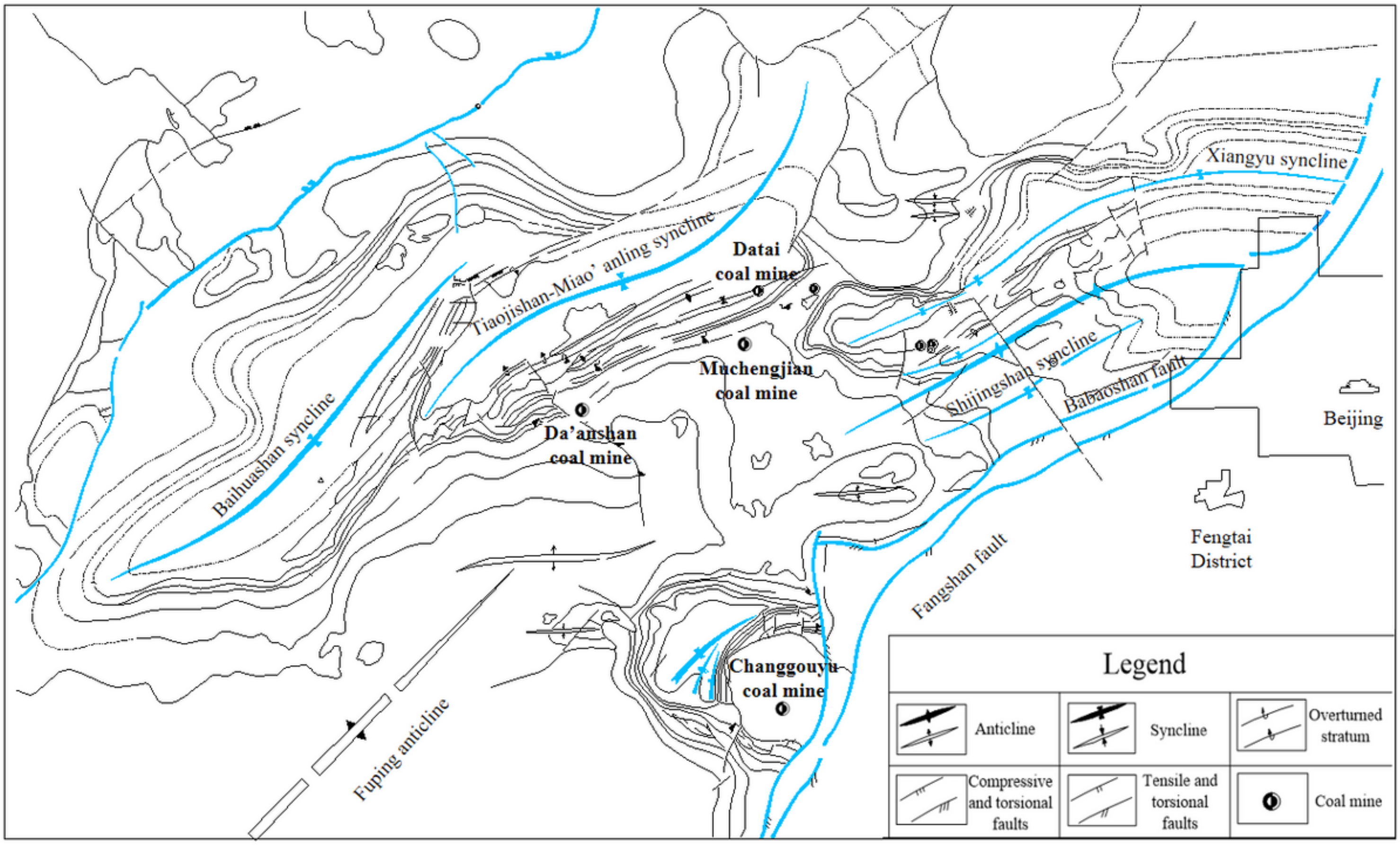


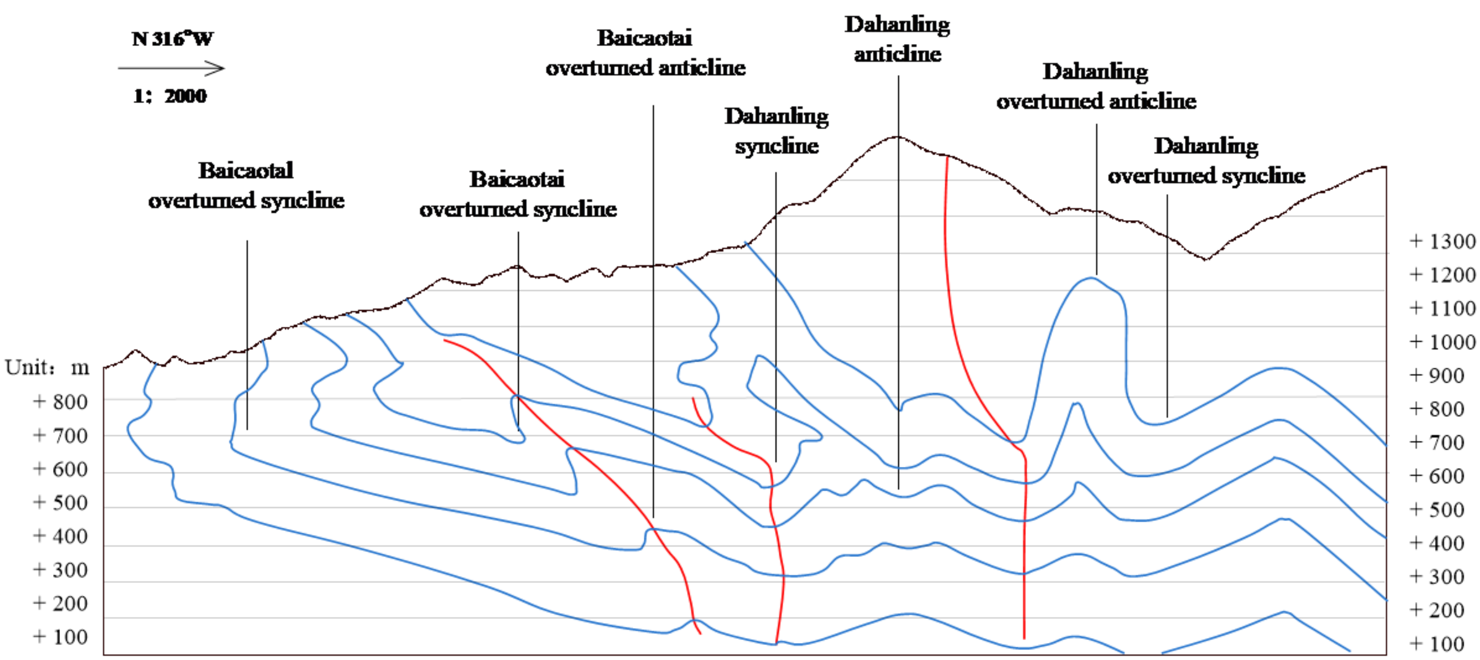

**Figure 8**

Normalized programming of multi-source data



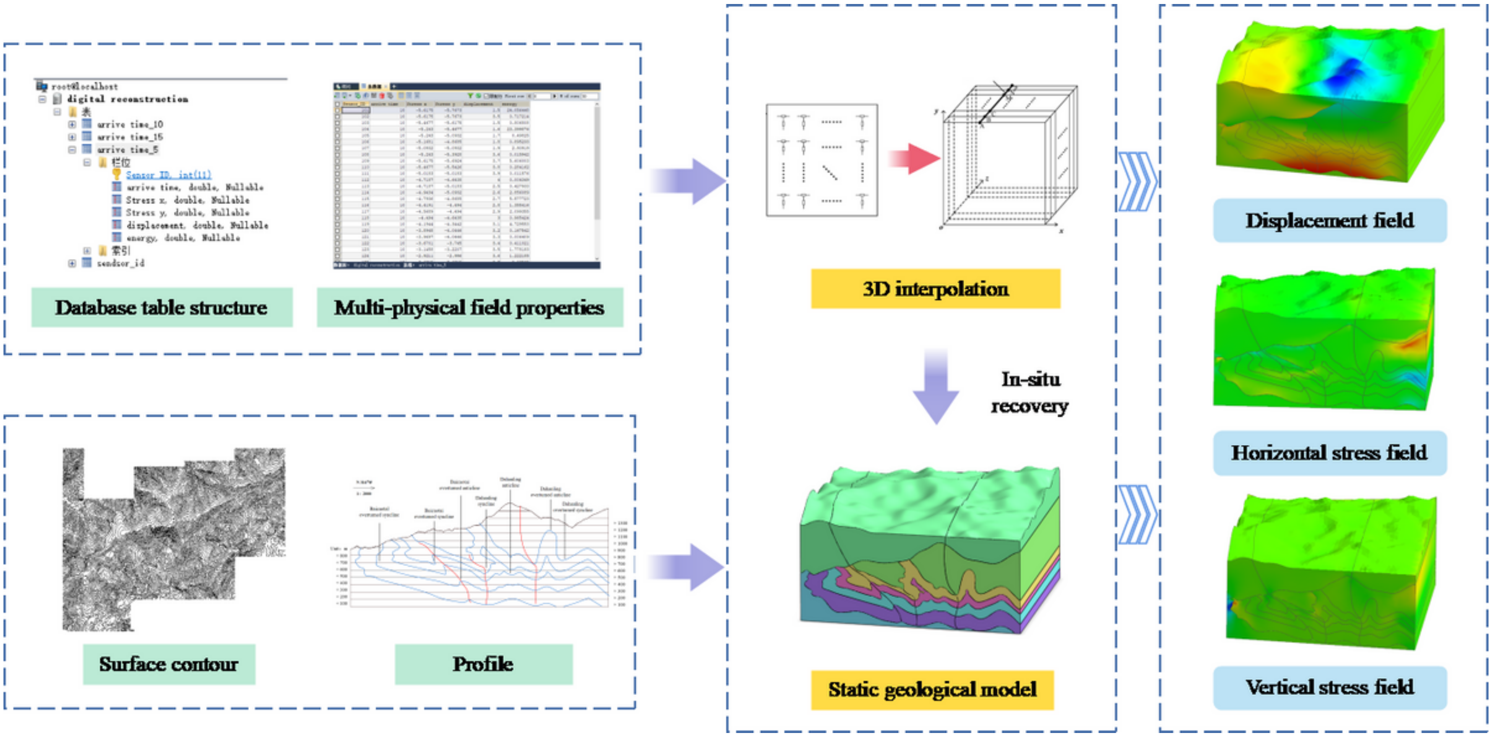

## Figure 9

Schematic map of geological structures in the mining area of western Beijing




## Figure 10

Tectonic section of the Da'anshan coal mine




### Figure 11

Digital reconstruction effect of Da’anshan coal mine