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Programmatic Numerical Simulation Modular Modeling Methodology

-- Engineering Applications of 3DEC

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Abstract: Aiming at the problem that programmatic numerical simulation involves tedious repeated input of commands and parameters as well as a large number of auxiliary calculations and operations, which is time-consuming and labor-intensive, this paper takes the gob-side entry driving with roof cutting pressure relief in Longquan Coal Mine as the engineering background, and discusses the connotation of the modular modeling concept for numerical simulation, as well as its application and effect in studying the above problem by using 3DEC 5.2 software. Decomposing the simulation process into several sub-modules can greatly improve the efficiency of model modification and parameter research. In the long run, the modular modeling concept and method can provide a "one-stop service" for parameter comparison research and cross-model development, thus saving substantial time and energy for researchers. Different simulation software packages have distinct programming techniques; therefore, we should adapt measures to local conditions and adopt an approach that integrates the modular modeling concept with the specific features of the simulation software in use.

Keywords: Modular Concept; Modular Modeling; Modular Programming; 3DEC;

1. Introduction

Modularity refers to decomposing a complex system into several independent yet interrelated sub-modules, each of which fulfills a specific function. All sub-modules are assembled according to problem-oriented logic to realize the overall function of the system. Modularity has transformed our world, with applications including modular furniture, modular management, modular manufacturing processes, modular architecture (prefabricated buildings), modularization of educational curricula, modular electronic circuits, modular software development, and modular marketing operations.

In the professional field of programming, the concept and technology of modular programming design have long yielded fruitful achievements. Kyung-Goo Doha[1] used action semantics to define and combine language modules. The modularity and scalability of action semantics helped us systematically develop programming languages, especially when there were existing language modules for similar languages. Only a few modifications were needed to design new language modules. Germano Schafaschek[2] proposed a supervised control approach for timed discrete event systems that allows for a local synthesis of modular supervision, with each control module considering only the subsystems affected by the corresponding control specification, making it easier to understand, implement, and modify the local manager. Pan Hu[3] proposes a new framework for modular materialization and incremental reasoning that supports materialization and incremental reasoning through a collection of modules, each responsible for deriving the results of a subset of programs, speeding up materialization and incremental reasoning by several orders of magnitude and significantly improving the scalability of Datalog reasoners. Eric Gascard and Zineb Simeu-Abazi[4] proposed a method for diagnosing complex systems based on communication time automata, where each component is individually modeled by a timing automaton and integrates various modes of operation. The communication between each component is carried out by the control module, which improves the availability of the system and reduces the maintenance cost. Hsing-Chih Tsai and Lin [5] proposed a modular neural network in which each modular element adopts a high-order neural network to create a formula that considers both weights and exponents. It makes the calculation more accurate, makes the programming formula more concise, and makes it possible to conduct parameter studies. Jack B. Dennis[6] believed that the construction of large software systems was always achieved through the assembly of independently written components program modules. Florian Gnad Florian Gnad[7] developed Proteus, and its main advantage was modularity. Proteus allowed the user to model complex systems by combining simpler components via a webbased ‘pick and choose’ approach. Liang Feng [8]which emphasizes isolating the functionality of a system into independent, interchangeable modules, to tailor the hierarchy and diversity in these complex systems.

Taking the engineering case of gob-side entry driving with roof cutting pressure relief at the 4110 working face of Longquan Coal Mine as the background, this paper elaborates on the application and key elements of the modular programming concept in the process of discussing the impacts of critical parameters—namely coal pillar width, roof cutting angle, and roof cutting length—on surrounding rock. For the same research problem, the modularization processes of three software packages (3DEC 5.2) are demonstrated. It is advocated that the modular concept be introduced into the compilation of simulation scripts to achieve the goal of improving simulation efficiency.

2. Traditional Modeling Workflow and Existing Problems

2.1. Traditional Modeling Workflow and Its Representation Forms

As shown in Fig. 1, this is the workflow of traditional numerical simulation modeling: modeling → parameter assignment → boundary condition modification → result comparison → model adjustment → re-parameter assignment → and so forth.

Such a modeling workflow can help beginners familiarize themselves with the basic modeling methods, master the operation skills of various commands, and understand the connection, arrangement and combination of each command.

As shown in Fig. 2, this is a typical script from the Getting Started section of the 3DEC 5.2 User's Guide. It can be observed that a typical characteristic of such a modeling process is the inclusion of a large volume of data within the script; however, these data points have inherent interconnections, which requires operators to perform extensive external calculations and then input the results into the commands. This significantly increases the workload of variable input and the probability of errors. What is even more problematic is model modification, which can be described as "a minor change leading to far-reaching impacts".

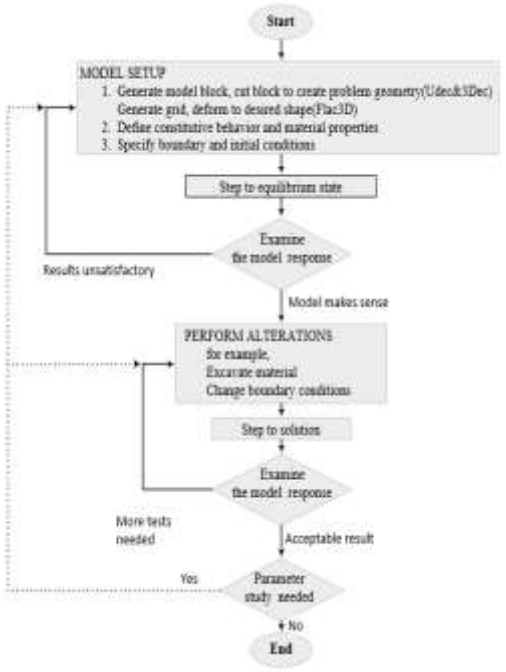


Fig. 1 Traditional modeling process

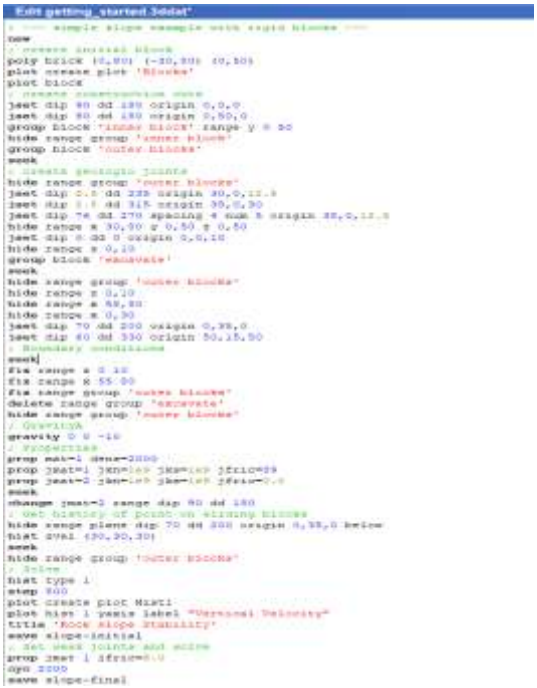


Fig. 2 Typical commands and variable input methods(3Dec)

2.2. Existing Problems of Traditional Modeling Workflow

This paper summarizes several inconsistencies between traditional modeling methods and efficient numerical simulation:

(1) As model complexity increases, variables grow accordingly. Traditional methods require numerous input functions and variables, leading to heavy external auxiliary calculation workload and substantial time/energy investment for simulators.

(2) Common commands or command combinations, along with their variables, need repeated input, increasing time cost and error risk. Error correction is also time-consuming.

(3) Unsatisfactory model design requires repeated adjustments of size and boundary conditions, each requiring re-conducted external auxiliary calculations.

(4) Unsatisfactory model results demand repeated adjustments of excavation, support and other variables, with correlated operations and calculations restarted.

(5) Exhaustive simulation, parameter testing and object research require numerous similar models, repeated trial calculations and adjustments, each involving the dilemma of re-entering numerous variables.

(6) Image extraction involves manual repeated file saving, window adjustment, naming and copying for comparison, requiring extensive auxiliary operations.

(7) Monitoring points and data need manual one-by-one layout and extraction, involving massive auxiliary data deletion and Excel-based graphing/comparison, resulting in heavy workload.

(8) Excellent modeling ideas and mature command combinations cannot be directly reused in subsequent models, leading to poor portability.

In summary, traditional simulation relies on repeated trial and error and extensive variable input. Multiple model comparisons make programming and modification time-consuming, labor-intensive, and even catastrophic, often failing to yield ideal results after months of work. This is a key barrier to advanced efficient numerical simulation.

3. Engineering Geological Conditions and Modular Technical Route

3.1. Extraction-Development Interface

Longquan Coal Mine is located in Loufan County, Taiyuan City, Shanxi Province, with the No. 4 coal seam being mined. The traditional practice of leaving a 30-meter-wide large coal pillar for roadway protection has resulted in massive waste of coal resources. To address this issue, it is planned to adopt the

roof cutting pressure relief gob-side entry driving method to reduce the width of coal pillars, thereby improving coal recovery rate. As shown in Fig. 3, the return airway of the 4114 working face is arranged at the edge of the gob of the 4112 working face.

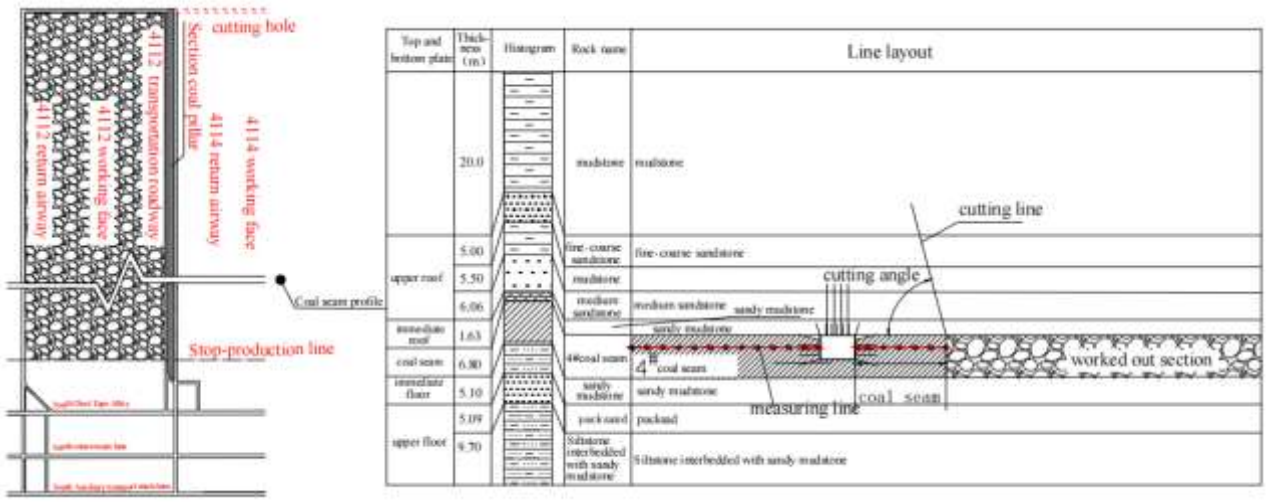


Fig. 3 Mining and Excavation Engineering Plan

3.2. Engineering Geological Conditions

As shown in Fig. 3, the No. 4 coal seam has a thickness ranging from 6.2 to 7.4 m with an average of 6.8 m and a dip angle between 4° and 8°; from bottom to top, its roof strata consist of dark gray sandy mudstone with an average thickness of 1.63 m, which features horizontal bedding, contains plant leaf fossils and is intercalated with thin ferruginous layers on the bedding planes, followed by grayish-white medium sandstone with an average thickness of 6.06 m that is cemented by argillaceous materials and bears abundant carbon particles on the bedding planes, then grayish-black mudstone with an average thickness of 5.50 m containing pyrite concretions and showing wavy bedding, next is grayish-white fine-to-coarse sandstone with an average thickness of 5.00 m dominated by quartz with occasional joints, and finally grayish-black mudstone with an average thickness of 20.0 m that contains incomplete plant fossils and displays wavy bedding; from top to bottom, the floor strata are composed of blackish-gray sandy mudstone with an average thickness of 5.1 m in massive structure, fine sandstone with an average thickness of 5.09 m that is dominated by quartz, cemented by grayish-black siliceous materials and contains disseminated pyrite, as well as interbedded grayish-black siltstone and sandy mudstone with an average thickness of 9.70 m that is cemented by calcareous materials and has poorly developed joints.

3.3. Research Aims and Simulation Plan

The research object is the evolution law of σv-σh stress on both sides of the roadway after roof cutting and gob-side entry driving, and the influencing factors include: coal pillar width, roof cutting angle and roof cutting depth.

Table 1 Simulation Plans of Different Coal Pillar Widths Post Roof Cutting

	Roof cutting length: 20 m; roof cutting angle: 75°;different coal pillar widths / m,										
Post-roadway-driving	30	25	20	18	16	14	12	10	8	6	4

As shown in Table 1, when the roof cutting length is 20 m and the roof cutting angle is 75°, the evolution law of σv-σh stress in the surrounding rock after roadway excavation is compared for the process of coal pillar width varying from 30 m to 4 m.

Table 2 Simulation Plans of Different Coal Pillar Widths Post Roof Cutting

	Coal Pillar Width (m) | Roof Cutting Length (m) | Roof Cutting Angle (°)										
Post-roadway-driving	30	25	20	18	16	14	12	10	8	6	4

As shown in Table 2, when the coal pillar width is 8 m and the roof cutting length is 20 m, the evolution law of σv-σh stress in the surrounding rock after roadway excavation is compared for the process of roof cutting angle varying from 90° to 50°.

Table 3 Simulation Plans of Different Coal Pillar Widths Post Roof Cutting

	Coal Pillar Width (m) | Roof Cutting Angle (°) | Roof Cutting Length (m)										
Post-roadway-driving	30	25	20	18	16	14	12	10	8	6	4

As shown in Table 3, when the coal pillar width is 8 m and the roof cutting angle is 75°, the evolution law of σv-σh

stress in the surrounding rock after roadway excavation is compared for the process of roof cutting length varying from 0 to 35 m.

It can be seen from the above simulation schemes that the number of models built amounts to dozens. If the conventional modeling method is adopted for analysis, the workload involved in model establishment, parameter adjustment, parametric study, data extraction and result comparison is beyond imagination.

3.4. Modular Modeling Process and Architecture

(1) Decompose the task into several sub-modules with clear functions. As shown in Fig. 6, this simulation can be divided into the following sub-modules: modeling method, boundary fixing method, constitutive relation parameter assignment method, working face excavation method, roadway excavation method, roof cutting and pressure relief method, anchor bolt (cable) layout method, image extraction method, monitoring data layout and extraction method, data visualization method, etc.

(2) Analyze the mathematical relationships between various variables and express them through standard functions and parameters. Centralize the model dimension parameters, calculation parameters, working face excavation parameters, roadway excavation parameters, support parameters, and roof cutting parameters as variables in the main program.

(3) Clarify the basic architecture and process. According to the on-site mining-excavation relationship and research objectives, determine the calling sequence of each sub-module, such as: modeling → initial equilibrium → working face excavation → cutting slot excavation → roadway excavation → support → batch drawing output → batch data output, etc.

(4) If the initial response of the model, excavation effect of the model, or monitoring results are unsatisfactory, or if analysis of the response to a certain parameter is required, it is only necessary to return to the main control program at the top to modify the relevant parameters, instead of modifying a series of associated variables inside the model.

The research parameters in this paper include: coal pillar width, roof cutting angle, and roof cutting length. The simulation results for the study of the corresponding parameters can be obtained only by modifying the corresponding parameters in the main control program.

4. 3DEC Modular Modeling and Analysis Process

Based on the modular modeling concept and method, 3DEC 5.2 was adopted to investigate the same problem, and the main control program is shown in Fig. 4. Only the most basic parameters need to be input, including elastic modulus, Poisson's ratio, cohesion, internal friction angle, tensile strength, dilation angle, lateral pressure coefficient, burial depth, excavation dimensions, roof cutting angle and length, etc.

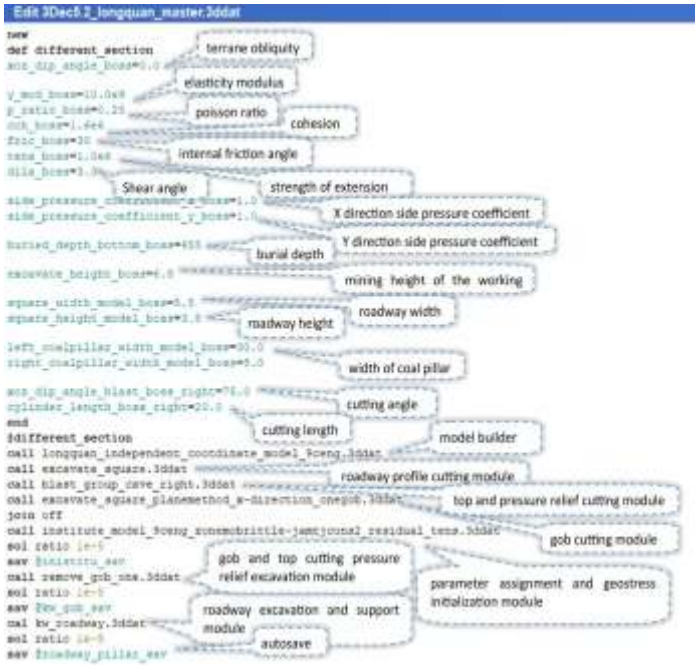
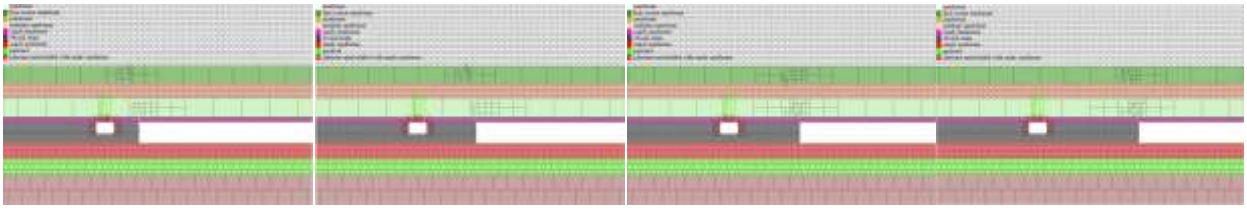


Fig. 3 Modular Main Control Program

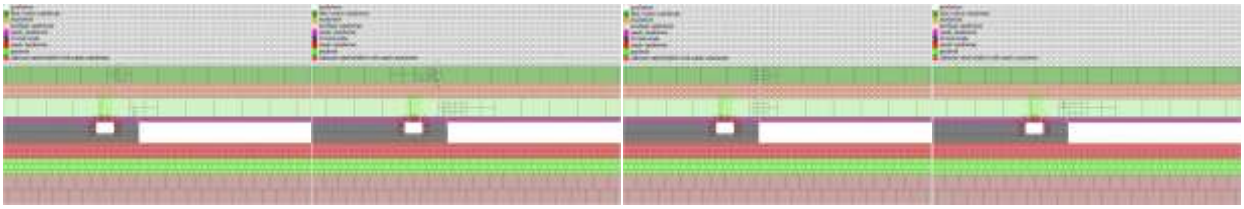
4.1. Modular 3DEC Model Establishment

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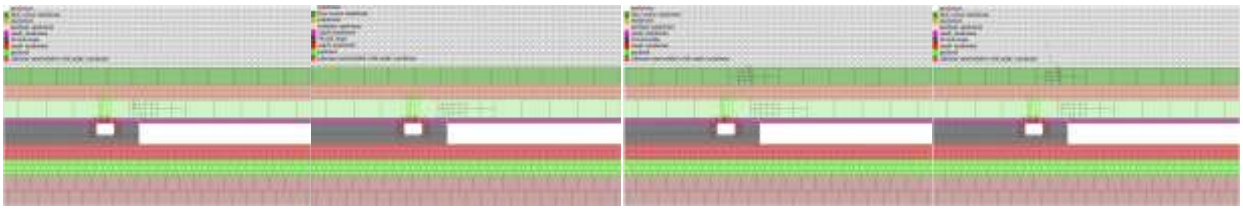
(a)Coal Pillar Width 8m (b)Coal Pillar Width 16m (c)Coal Pillar Width 20m (d)Coal Pillar Width 30m

Fig. 4 Gob-side Entry Driving Model Diagram for Different Coal Pillar Widths Post Roof Cutting



(a)Roof Cutting Angle 60° (b)Roof Cutting Angle 70° (c)Roof Cutting Angle 80° (d)Roof Cutting Angle 90°

Fig. 5 Gob-side Entry Driving Model Diagram for 8 m Coal Pillar Width with Different Roof Cutting Angles



(a)Roof Cutting Length 5m (b)Roof Cutting Length 10m (c)Roof Cutting Length 20m (d)Roof Cutting Length 30m

Fig. 6 Gob-side Entry Driving Model Diagram for 8 m Coal Pillar Width with Different Roof Cutting Lengths

By modifying only parameters such as coal pillar width (right_coalpillar_width_model_boss), roof cutting angle (direction_xoz_dip_angle_boss), and roof cutting length (blast_length_model_boss) in the main control program, a series of models can be generated. Due to space limitations, as shown in Fig. 4, Fig. 5 and Fig. 6, only partial 3DEC model diagrams with different coal pillar widths, different roof cutting angles and different roof cutting lengths are listed.

By invoking the image extraction sub-module of 3DEC 5.2, the σv-σh nephograms are extracted and arranged in the sequence specified in the simulation scheme. only partial results are listed herein. The results can be quickly browsed and compared in the large-image view or slide mode under the corresponding folder, which eliminates auxiliary operations such as exporting images one by one and manually naming each image individually.

A data extraction and visualization module for 3DEC 5.2 was developed. Data are extracted from different 3dsav files in a prearranged sequence and position, and stored in Excel. The results of parametric studies can be quickly previewed simply by opening the Excel file, such as the σv-σh curves on both sides of the roadway. Other physical quantities can also be exported simultaneously, including: sxx (horizontal stress), s1 (maximum principal stress), s2 (intermediate principal stress), s3 (minimum principal stress), ssmax (maximum shear stress), szz (vertical stress), zdis (vertical displacement), dis (total displacement), etc., which are not listed exhaustively. This module also supports independent operation and embedding into the main program.

5. Summary

(1) The modeling method guided by the modular concept of numerical simulation combines the advantages of structured programming and object-oriented programming. It can effectively reduce the time spent on modifying models such as parameter assignment, parameter adjustment, and parametric studies, with the effect becoming more pronounced as the workload increases. It enables the generation of a single model by modifying one parameter, and the acquisition of a series of post-processing charts and tables by changing a set of parameters. The entire process can run unattended, with the system shutting down automatically upon completion, and results can be viewed at any time.

(2) Considerable effort is required to "black-box" the preliminary sub-modules. In the long run, the advantages of the modular modeling method far outweigh its disadvantages.

(3) Each sub-module operates independently in a "black-box" mode with clear functions and definite internal relationships. When a single module fails to work properly, it is only necessary to check the interface parameters of the module, rather than troubleshooting the internal part of the module.

(4) Each "black-box" sub-module features interchangeability, universality, and standardization, with flexible external connection relationships. They are portable, support secondary development, and can realize cross-model invocation. For example, the anchor bolt (cable) layout module, image extraction module, monitoring point layout module, monitoring data extraction module, and data visualization module can all be reused in other mining

simulations by simply connecting to standard interfaces, which will greatly improve the modeling and data processing speed of subsequent mining-related models.

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