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Review Article

Dynamic Stability Analysis of Rockmass: A Review

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There are a series of human or natural activities, including earthquakes, explosions, and rockbursts, which have caused a number of safety accidents in geotechnical engineering. This review paper summarized the theories and methods for dynamic stability analysis of rockmass. First, numerical simulation methods, including finite element method (FEM), discrete element method (DEM), finite difference method (FDM), boundary element method (BEM), discontinuous deformation analysis method (DDA), and numerical manifold method (NMM), are summarized. Second, the laboratory experiments, containing shaking table test, split-Hopkinson pressure bar test (SHPB), improved true-triaxial test, dynamic centrifugal model test, acoustic emission (AE) technique, and dynamic infrared monitoring, are considered. Third, the in situ tests including microseismic (MS) technique, velocity tomography, stress-strain monitoring, and electromagnetic radiation monitoring are considered. Finally, some comprehensive analysis methods based on statistical theories are also provided. It is pointed out that the study foundation for the dynamic stability of rockmass is weak to explain the mechanism. So, a set of general comprehensive theories integrating the different methods, including theoretical analysis, numerical methods, laboratory experiments, and in situ tests, should be completely established. This is the most effective way for further investigation.

1. Introduction

The dynamic stability of rockmass is mainly in the aspects of earthquakes, explosions, and rockbursts. The threats of earthquakes and their associated geological disasters such as landslides to mankind have lasted for thousands of years. Under the influence of large magnitude earthquakes including Wenchuan earthquake [1] and Ya'an earthquake [2], people have realized the urgency and importance of the study on structural stability under seismicity [3, 4]. Because of the diversity and complexity of earthquakes, prediction of earthquake is very difficult. The researches on the failure mechanism of geotechnical engineering including slopes, underground adits, and other geotechnical engineering under the seismic condition provide a scientific reference for the selection of engineering seismic performance, which is currently the hotspot in rock mechanics.

The explosions have great influence on geotechnical engineering, such as the stability of tunnels and slopes. The impact of the explosions on the rockmass is mainly caused by the stress wave generated by the explosion stress wave and the explosive gas. Harmful gases from explosions can affect mine production and environment [5]. The stress effect of the explosive gas cannot be ignored. To solve this problem, gas pressure can be considered as a quasi-static process [6, 7]. It has a certain impact on the living environment of residents near construction sites [8, 9]. Besides, the seismicity caused by the explosions may lead to the collapse of the goafs and seriously threaten the mine production [10, 11]. Most of the common explosions are due to chemical explosions caused by detonation of explosives. In order to reduce the environmental pollution caused by the explosions of toxic and harmful gases, CO_2 blasting has been gradually developed in the fields of mining engineering and geotechnical engineering [12–14].

The effect of shock wave and explosive gas on rockmass is shown in Figure 1.

Rockbursts are common disasters in underground engineering of high stress [15, 16]. When the rockburst occurs, the energy releases sharply, which makes the surrounding rockmasses suddenly broken under unknown conditions. It threatens the construction workers, underground equipment, and building safety. Rockbursts can be divided into two types: strain rockburst and impact rockburst. Both phenomena occur on the surfaces of the rockmasses, but the sources of force and time are different [17]. Rockbursts in coal mines have a large degree of damage and a wide range of influences, which may lead to serious disasters such as gas explosions [18]. Furthermore, rockbursts can cause fire, water inrush, and the destruction of the ventilation system, which are of great concern in rock dynamics [19–22].

It is obvious that numerical simulation software, including ANSYS, ABAQUS, UDEC, 3DEC, FLAC, and PFC, have contributed greatly to the application of numerical simulation methods to the study of rock and soil mass [23–27]. In addition, in terms of experimental instruments, several advanced testing machines such as MTS and Instron series of rock mechanics large-scale testing machines have been manufactured to meet the needs of scientific researches. Besides, in situ tests containing MS technique, velocity tomography, stress-strain monitoring, and electromagnetic radiation monitoring have been improved dramatically. Furthermore, some comprehensive analysis methods based on statistical theories including the Bayesian network are constantly considered. However, it must be clearly realized that there are many theories and methods to be improved, such as the standardization of numerical simulation and the technological improvement of experimental equipment. Fortunately, more manpower and material resources are invested, which has contributed greatly to the researches on the dynamic stability of rockmass.

This review aims at providing several theories and methods to dynamic stability analysis of rockmass. First, the numerical simulation methods (including FEM, DEM, FDM, BEM, DDA, and NMM) are summarized; then, some laboratory experiments and in situ tests are considered. Moreover, some comprehensive analysis methods based on statistical theories are described. Finally, a brief summary and some prospective researches are presented.

2. Numerical Simulation Methods

2.1. Finite Element Method (FEM). FEM was developed because of the variational principle in the early stage. In the 1950s, FEM was used to realize the mechanical analysis of the aircraft. At the same time, large-scale electronic computers were put into the work of understanding the large-scale algebraic equations. Around 1960, Clough and Feng proposed "finite element," and the finite element technology was born [28].

FEM is a numerical analysis method that obtains approximate solutions to engineering problems. It replaces the real structure with a discrete set of finite elements. Through the analysis of elements, the approximate solution of the entire structure is obtained. In the engineering design, this approximate solution can meet the needs of the project with sufficient accuracy.

The process of finite element analysis is to divide the complex geometric and force objects into elements with relatively a simple shape and then give the displacement and force description of the element nodes. Next, the element stiffness equation is constructed. Then, by the assembly of the element through the node connection relationship among the elements, the overall rigidity equation of the structure can be obtained. Finally, according to the displacement constraints and stress conditions, the boundary conditions are processed and the solution is found [29]. The schematic diagram of the basic process is shown in Figure 2.

FEM is widely used in the analysis of rockmass dynamic stability. The commonly used finite element software includes ANSYS (LS-DYNA), ABAQUS, and ADINA. Besides, some new development software, like RFPA, was developed for rockmass instability rupture and stability under dynamic and static loads [31–34]. Secondary development based on commonly used numerical simulation programs was also carried out. Some applications of the FEM in dynamic stability analysis of rockmass are summarized in Table 1. FEM is more mature in the field of numerical simulation, and the calculation is stable and reliable, so it has a wide range of applications.

FEM is widely used because it allows every element to have different shapes and material properties, has the advantages of strong geometric adaptability and flexibility to handle different physical parameters [50]. However, the spatial derivative of FEM physical quantity is obtained by deriving the shape function, so the accuracy is lower by one degree than the physical quantity itself. The finite element analysis is greatly affected by the mesh. When analyzing the complex model, the finite element mesh may be deformed and overlapped, which affects the calculation accuracy.

2.2. Discrete Element Method (DEM). DEM was proposed by Cundall in 1971 [51]. It is suitable for studying the mechanical problems of joint systems or block assemblies under quasi-static or dynamic conditions. Initially, DEM was used to analyze the motion of rock slopes. Later, Cundall and Strack developed the BALL program for simulating two-dimensionally circular blocks of granular media and obtained results that were very consistent with experiments using photoelastic technology [52]. There were many results that had been achieved in research and application of DEM.

DEM is a numerical simulation method specifically designed to solve the problem of discontinuous media. Rocks and structural planes with different properties constitute the basic components of the rockmasses. DEM describes the two basic components of rockmasses by the laws of continuum mechanics and contact, in which the structural planes are the boundaries of the rocks. A single rock is used as an independent object for mechanical analysis. The forces and displacements are transmitted through the structural planes and other adjacent rocks.

The general solving processes of DEM are as follows: first of all, combined with the actual problem, the research object

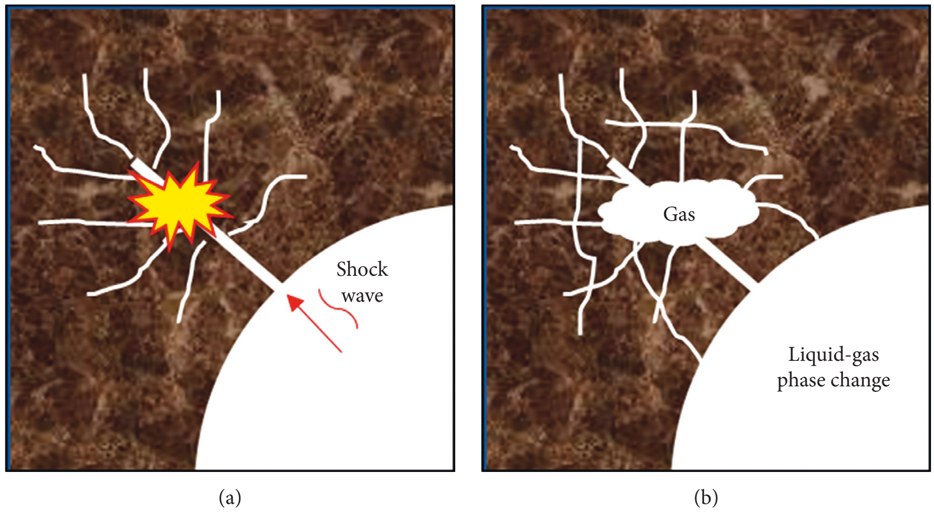

FIGURE 1: (a) The shock wave causes longitudinal cracks, and (b) the explosive gas expands to cause lateral cracks, thereby destroying the rockmasses.

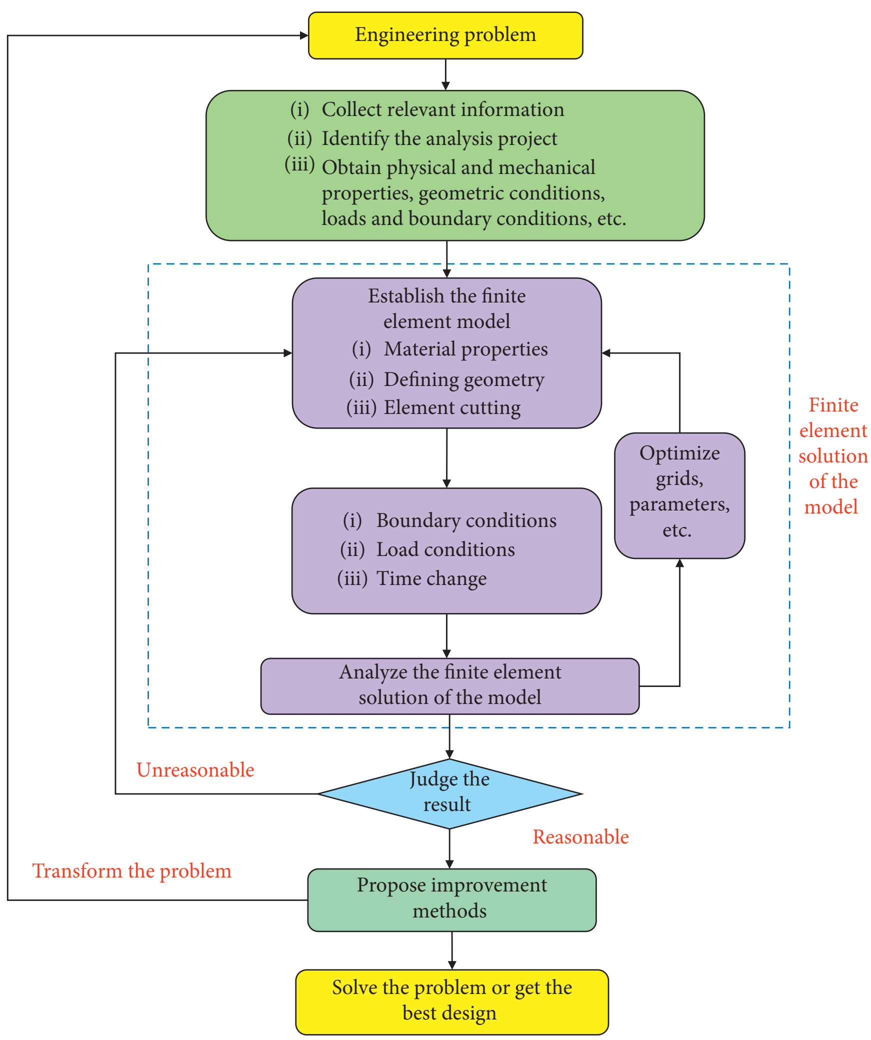

FIGURE 2: The basic process of FEM (revised from [30]).

Table 1: Applications of the FEM in dynamic stability analysis of rockmass.

Classifications	Software	Titles	Authors
Earthquake	ADINA	Seismic stability of subsea tunnels subjected to seepage	Cheng et al. [35]
Earthquake	ANSYS	New methods of safety evaluation for rock/soil mass surrounding tunnel under earthquake	Cheng et al. [36]
Earthquake	ABAQUS	A new continuum based model for the simulation of a seismically induced large-scale rockslide	Shirole et al. [37]
Earthquake	VC++, ASLS	Numerical and experimental investigation on the stability of slopes threatened by earthquakes	Jiao et al. [38]
Earthquake	TFINE	Stability analysis of earthquake-induced rock slope based on back analysis of shear strength parameters of rock mass	Lv et al. [39]
Earthquake	ABAQUS	Wave propagations through jointed rock masses and their effects on the stability of slopes	Che et al. [40]
Earthquake	TFINE	Dynamic limit equilibrium analysis of sliding block for rock slope based on nonlinear FEM	Liu et al. [41]
Earthquake	RFPA3D	The dynamic evaluation of rock slope stability considering the effects of microseismic damage	Xu et al. [42]
Earthquake	SUCED	Analysis of seismic damage of underground powerhouse structure of hydropower plants based on dynamic contact force method	Yang et al. [43]
Earthquake	ABAQUS	Seismic response of a large underground rock cavern groups considering different incident angles of earthquake waves	Zhao et al. [44]
Earthquake	Phase2	Geotechnical investigations and remediation design for failure of tunnel portal section: a case study in northern Turkey	Kaya et al. [45]
Earthquake	Plaxis2D	Stability analysis of a slope subject to real accelerograms by finite elements. Application to San Pedro cliff at the Alhambra in Granada	Morales-Esteban et al. [46]
Explosion	ANSYS/LS-DYNA	Numerical simulation of rock mass damage evolution during deep-buried tunnel excavation by drill and blast	Yang et al. [47]
Explosion	ANSYS/LS-DYNA	Propagation and prediction of blasting vibration on slope in an open pit during underground mining	Jiang et al. [48]
Explosion	ANSYS/LS-DYNA	Numerical simulation of blast vibration and crack forming effect of rock-anchored beam excavation in deep underground caverns	Li et al. [49]

is discretized into an element array, and the elements are connected by reasonable connection methods. Then, the relationship between the forces and the relative displacements can be used to obtain the normal and tangential forces between the elements. Additionally, the forces acting in all directions among the elements and other external forces acting on the elements are combined, and the acceleration of the elements can be obtained according to the second law of Newton's motion. The acceleration is integrated to obtain the velocity and displacement of the elements. Thereby, physical quantities such as speed and acceleration of all the elements at any time are obtained [53].

DEM has been developed for several decades, and the corresponding simulation software is constantly developing and improving. In 1980, the ITASCA Consulting Group from the United States developed DEM software UDEC and launched it on the market [54]. Lorig et al. [55] developed a discrete element-boundary element coupling calculation program. The PFC developed by the ITASCA Consulting Group from the United States is also widely used. Since its debut, DEM has been widely used in the field of geotechnical engineering. With the in-depth study of rockmass dynamic stability problems, DEM has received widespread attention because of its characteristics. Some applications of the discrete element method in dynamic stability analysis of rockmass are summarized in Table 2. DEM is more fitting to the simulation analysis of broken rockmass. With the continuous improvement of this method, it obtains much applications in rockmass dynamic stability analysis.

DEM has a good effect on the study of joint cracks and dynamic problems in engineering. However, DEM has certain deficiencies, and its theoretical method still needs improvement. Most of the methods used are explicit algorithms, and the problems of error transfer brought about by continuous accumulation. The calculation speed of DEM has a great relationship with the division of the elements, and the more the elements and contact surfaces, the greater the amount of calculations. Therefore, when simulating large-scale engineering problems, it takes a lot of time.

2.3. Finite Difference Method (FDM). FDM originated from the research results of Southwell (1940) and Otter (1966) and has a long history of development. It is mainly used to analyze stress and deformation in rockmasses. Itasca applied FDM to develop FLAC and FLAC3D for stress and deformation analysis of rock and soil masses. It has a wide range of applications in geotechnical engineering and mining engineering.

The basic idea of FDM is to use differential meshing to solve the discrete solution of the domain. The differential equation is used to convert the scientific control equation into the difference equation through the difference formula. The initial conditions and boundary conditions are used to solve the linear equations, and then, the initial and boundary conditions are combined to solve the linear equations.

Table 2: Applications of the discrete element method in dynamic stability analysis of rockmass.

Classifications	Software	Titles	Authors
Earthquake	UDEC	Numerical simulation of dynamic stability of slope rock mass under seismic loading	Tan et al. [56]
Earthquake	3DEC	Seismic response of underground rock cavern dominated by a large geological discontinuity subjected to near-fault and far-field ground motions	Cui and Sheng [57]
Earthquake	PFC3D	Simulation and analysis of earthquake stability for open-pit coal mine slope	Cui et al. [58]
Earthquake	PFC2D	Simulation of dynamic failure process of horizontal thick-layered rock slopes using particle flow code	Hu et al. [59]
Earthquake	UDEC	Dynamic stability evaluation for rock structure around underground cavern based on frictional energy on joints	Wang et al. [60]
Earthquake	UDEC	Numerical modeling of wave transmission across rock masses with nonlinear joints	Li et al. [61]
Earthquake	UDEC	Dynamic model of fracture normal behavior and application to prediction of stress wave attenuation across fractures	Zhao et al. [62]
Earthquake	UDEC, SuperFLUSH/2D	Estimation of dynamic behaviors of bedrock foundation subjected to seismic loads based on FEM and DEM simulations	Yang et al. [63]
Explosion	PFC3D	Simulated study on the influence of the slope blasting height on the slope stability	Cui et al. [64]
Explosion	3DEC, LS-DYNA, FLAC3D	Rock damage control in bedrock blasting excavation for a nuclear power plant	Li et al. [65]
Explosion	PFC2D	Dynamic stress concentration and energy evolution of deep-buried tunnels under blasting loads	Li et al. [66]

FLAC and FLAC3D are intended to analyze the problem of continuous media or media with very sparse joints. They use explicit finite difference techniques to solve the problem domain control equations. Explicit finite difference techniques means that the unknown quantity of the problem can be determined step by step according to the steps of each difference equation directly through the known quantity. With this method, a large matrix does not need to be formed during the analysis, so the need for computer storage space can be reduced. The value is relatively stable during the calculation process, and the iterative solution process is optimized. In addition, the method also considers initial conditions, boundary conditions, and constitutive equation of the medium. The FLAC3D numerical model construction and simulation analysis is shown in Figure 3.

FDM has been applied to simulate and analyze the rockmass dynamics problem. Based on the engineering practice, combined with FLAC3D, the mining kinetics behavior of coal and rockmass under different propulsion speeds was studied [67]. FLAC3D was applied to study the displacement characteristics of underground adits under earthquake loads and analyze the response characteristics of underground adits under consistent/nonuniform ground motion input conditions [68, 69]. The FLAC/PFC2D-coupled calculation model was applied to study the mechanism of seismic failure of the reversed rock slope [70]. The stability of a broken chamber in the Dongguashan copper mine under dynamic load conditions was analyzed [71]. The dynamic response of horizontally layered rock slope under SV wave action was researched by FLAC [72]. Besides, Zheng et al. [73] used FLAC3D to analyze the stability of the anchor system under blasting impact loads. Mortazavin and Alavi [74] used FLAC3D to study the effect of the full-shotcrete anchor support on surrounding rock under dynamic loading. Srikrishnan et al. [75] used FLAC3D to study the failure mechanism of the slope under earthquake loads. Probabilistic statistics and FLAC3D were used to analyze the dynamic stability and failure mechanism of the slope [76]. FDM plays a certain role in dynamic stability analysis.

Numerical simulation software FLAC and FLAC3D for FDM have the following advantages:

(1) They are suitable for progressive failure and instability of rock and soil, as well as large deformation analysis.

(2) Using the dynamic equations of motion makes them not to encounter numerical difficulties when dealing with unstable problems.

(3) The loads in any direction can be arbitrarily applied.

(4) It is more reasonable to simulate plastic fracture and plastic flow than FEM by the mixed discrete method.

(5) They are more comprehensive in their response to displacement changes and failure modes.

(6) Using explicit solution, there is no need to store the stiffness matrix, which significantly saves memory and computation time compared to the usual implicit solution [77].

At the same time, there are also several disadvantages:

(1) Simplification of boundary conditions and material properties has an impact on the analysis results.

(2) Most of the models are built by data files, and they cannot directly judge the rationality of the data inputted by the users. The preprocessing functions

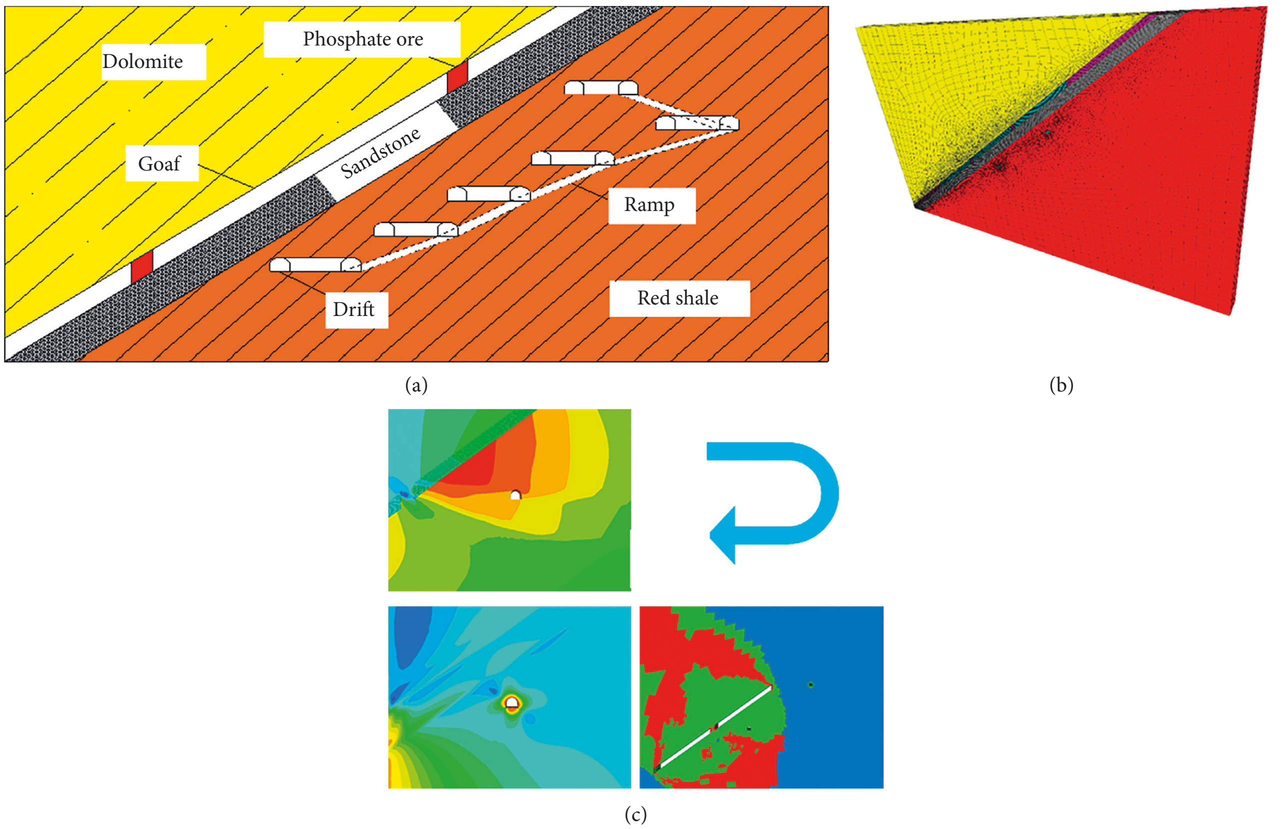

Figure 3: FLAC3D numerical model construction and simulation analysis: (a) the spatial distributions for the components of a stope; (b) the established model; (c) displacement, stress, and plastic zone analysis.

need to be improved. For complex engineering problems, it is often helpful to use some finite element software when building models and meshing [77].

(3) The modeling workload is large and time-consuming, which lengthens the simulation cycle and increases the simulation difficulty [77].

2.4. Boundary Element Method (BEM). BEM is a relatively accurate and effective numerical method after FEM [78]. After several decades of development until 1978, Brebbia held the first International Boundary Element Method Conference in Southampton, England, and published the monograph "The Boundary Element Method for Engineers" [79]. The boundary integral equations are derived using the weighted residual method, and it is pointed out that the weighted residual method is the most common numerical method. At this point, the name of the boundary element method has been internationally recognized.

The solution steps of BEM are as follows: first, the elements are divided on the boundary; second, the boundary integral equations are transformed into linear algebraic equations; third, the boundary value is solved to be determined at each boundary element; finally, the function value of any point in the calculation area can be found by using the analytical formula that relates the boundary value to the function value in the domain.

BEM can be divided into two basic types: the direct method and the indirect method. The direct method is to establish boundary integral equations using variables with explicit physical meanings, while the indirect method uses ambiguous variables. The virtual stresses and the virtual displacements are applied as basic unknowns to the boundaries according to certain rules. By establishing discretized equations, these variables are calculated, and then the displacements and stresses in the boundaries and regions are obtained [80].

BEM is used less independently in the field of rockmass dynamic stability and is often combined with other methods. Zhang et al. [81] used the singular BEM based on the manifold element to simulate the crack propagation of gravity dams during earthquake damage. Yin et al. [82] combined the idea of the viscoelastic boundary with BEM to establish the artificial boundary conditions of BEM to eliminate the reflection of seismic waves on the boundaries of the computational domain. BEM simplifies the research problems, reduces the error caused by discretization, and has a relatively small amount of calculation. For this reason, it is receiving increasing attention.

BEM has great advantages in solving problems including contact, fracture mechanics, motion boundary, infinite domain, semi-infinite domain, and ultrathin structure. In many application areas, BEM is recognized as an important complement to FEM. BEM also has many problems: singularity problems, full-coefficient matrix problems, domain integral problems in nonlinear and nonhomogeneous problems, thermal radiation and related coupling problems, and composite media problems [83].

2.5. Discontinuous Deformation Analysis (DDA). DDA was proposed by Shi [84, 85] in the 1980s. It was developed specifically to simulate the movement of discrete rockmass systems [86]. DDA is similar to FEM for solving the stress-displacement problem but considers the problem of large distribution of cracks and joints in the rockmasses, especially the interaction of the rock blocks along the discontinuous surfaces. DDA is usually expressed as the working energy method, which can be derived using the principle of minimum potential energy or the Hamiltonian principle. DDA uses the step-by-step approach to solve large displacement problems caused by discontinuous motion between blocks. Because this method considers the inertial force of block quality, it can be used to solve the full dynamic problem of mass movement.

DDA has been used to analyze the impact of rockmass dynamic problems, especially the effect of earthquakes on the stability of rockmass. In order to study the influence of near-fault seismic forces on landslides, Zhang et al. [87] used the discrete dynamic numerical analysis method DDA to simulate the motion characteristics of the landslide body. Zhang et al. [88] used the improved DDA method to study the seismic dynamic response of the underground powerhouse of the Dagangshan hydropower station in western China. Huang et al. [89] used the improved DDA method to analyze the Donghekou landslide triggered by the 2008 Wenchuan earthquake. Fu et al. [90] used DDA to analyze the seismic dynamic responses of underground adits.

The continuous research of DDA makes this method more mature and more suitable for large deformation analysis in geotechnical engineering. DDA combines the static analysis with dynamic analysis and has a complete block dynamics theory, making it capable of handling structural engineering, rock mechanics, and material analysis. However, because of the short development time of DDA, this method exposes some deficiencies in the specific application. The investigation and analysis of structural planes are neglected when studying DDA [91]. Moreover, deformation of the structural planes cannot be ignored in the deformation of blocks. These problems should be emphasized in research [92].

2.6. Numerical Manifold Method (NMM). NMM has been proposed by G. H. Shi in 1992 that deals with both continuous and discontinuous problems. The core and most innovative feature of NMM is the adoption of two coverage systems which include mathematical coverage (MC) and physical coverage (PC). MC can be considered as the union of a series of mathematical elements, and it must cover the entire physical area. Similarly, physical coverage is the union of all physical slices within a physical area [93].

NMM is regarded as a numerical method in the new century and has an excellent development prospect [85]. Because the NMM can deal with both continuous and noncontinuous problems, it is extremely suitable for simulating the deformation law of jointed rockmasses, and it has developed rapidly in the field of rock mechanics and engineering.

NMM has many limitations. For example, there are many difficulties for the NMM method from 2D to 3D to be solved; it lacks the ability to solve the nonlinear problems of the rockmass; and the practical application of engineering problems is insufficient [94]. Therefore, the modified NMM is used for rockmass dynamic analysis. Zhao et al. [95, 96] extended NMM to study wave propagation across rockmasses and developed a continuum-discontinuum-coupled model to simulate rock failure under dynamic loads. Qu et al. [97, 98] used the improved NMM to evaluate the dynamic stability of fractured rockmass slopes under seismic action. Wu and Wong [99] studied the collapse instability caused by joints or mining fissures in underground adits or tunnels using the numerical method. NMM integrates some advantages of the continuous FEM and the discontinuous DDA. In order to break through the limitations of the interelement correlation conditions, a great deal of effort in the study of the combination of the meshless method and NMM has been invested [100–102], making the NMM method able to achieve considerable development in rockmass stability analysis.

2.7. Comparison of Several Numerical Simulation Methods. Due to low cost and suitability for solving rockmass stability problems that are not suitable under many current experimental conditions, numerical simulation methods have been widely applied. Different numerical simulation methods have a different applicability to different engineering problems. Therefore, to study the dynamic stability problems of different rockmasses, choosing different numerical simulation methods has a certain influence on the reliability of the analysis results.

In addition, a variety of numerical simulation methods are used to accurately analyze the problems. For example, BEM is used to consider the influence of far-field stress to simulate the elastic properties; FEM is used as an intermediate transition to consider plastic deformation; and DEM is used to consider the near-field discontinuous deformation [103]. The concept of permanent displacement was proposed, and various numerical simulation software (including FLAC, UDEC, 3DEC, and DDA) were combined to study the stability of the slope under the action of earthquake loads [104]. Besides, FEM and DEM were applied to analyze the effect of force on collision of materials [105]. Furthermore, FLAC, ABAQUS, and engineering practice were combined to study the dynamic design method of deep hard rock tunnels [106]. For this reason, it is very necessary to develop a more general theory and method of numerical simulation, which needs comparing commonly used numerical simulation methods as the first step.

FEM is relatively mature in development and has a wide range of analysis software, represented by ANSYS/LS-

DYNA, ABAQUS, ADINA, etc. It is suitable for above medium hardness, small deformation rockmasses, which are not be discontinuously damaged. However, the accuracy of FEM calculation needs to be improved. DEM has been in development for decades. The simulation software is constantly being improved, represented by UDEC, 3DEC, and PFC from Itasca. It is suitable for above medium hardness, low stress level, and large deformation rockmasses. However, DEM has deficiencies, the theoretical method does not form a complete system, the calculation amount is large, and the precision needs to be improved. FDM has a long history of development, with the software represented by FLAC and FLAC3D from Itasca. It is suitable for weak and deformed rockmasses. However, the preprocessing functions of FLAC and FLAC3D are weak. Besides, the application of FDM in rockmass dynamics analysis is not mature enough. BEM is a relatively accurate numerical method after FEM. It is suitable for above medium hardness—small deformation rockmasses—which are not be discontinuously damaged. However, it is rarely used in rockmasses dynamics analysis. DDA has been applied in the dynamic stability of rockmasses and is constantly maturing. It is suitable for large deformation analysis in geotechnical engineering and discontinuous failure of rockmasses. However, DDA application time is short, and there is a problem of ignoring the role of the structural plane. NMM is a numerical method with good development prospects in the new century. It is suitable for above medium hardness and continuous or discontinuous deformation rockmasses. However, the development of NMM is not mature enough, so it often needs to be corrected. A comparison of several numerical simulation methods is shown in Figure 4.

3. Laboratory Experiments on Rockmasses under Dynamic Load

Due to its instability and other reasons, rockmasses are difficult to accurately measure through the sites. Therefore, in addition to the commonly used numerical simulations for dynamic stability analysis, laboratory experiments combined with similar models have become common methods [108]. Commonly used experimental methods include the shaking table test, split-Hopkinson pressure bar test (SHPB), improved true-triaxial test, dynamic centrifugal model test, and AE technique, and dynamic infrared monitoring.

3.1. Shaking Table Test. By inputting seismic waves to the shaker table and stimulating the reaction of the structure on the shake table, the seismic process can be reproduced well and artificial seismic wave experiments can be performed [109–111]. The experiment should follow the principle of similarity ratio [112]. It is the most direct method for studying the structural earthquake response and failure mechanism in the laboratory. The technology of the shaking table test is also improving. A new real-time substructuring technique for the shaking table test was proposed [113]. It has played a very important role in the field of marine structural engineering, hydraulic structures, and mining engineering related to rockmass dynamics [114–116]. Because the shaking table test has the characteristics of simple operation, high efficiency, and so on, its application field is expanding. This method is one of the important means in the current seismic research [117, 118].

3.2. Split-Hopkinson Pressure Bar Test (SHPB). The principle of the test is to clamp the specimen between two slender elastic rods (incident rods and transmissive rods), and the cylindrical bullet impacts the other end of the incident elastic rod at a certain speed, and then a compressive stress pulse is generated and propagated along the incident elastic rod in the direction of the sample [119–121]. When the stress waves are transmitted to the interface between the incident rod and the specimen, part of them are reflected back to the incident rod, and the others are loaded on the specimen and transmitted to the transmissive rod. The incident pulse, reflected pulse, and transmitted pulse can be recorded through the strain gauges attached to the incident and transmissive rods. One-dimensional stress wave theory can determine the stress, strain rate, strain change over time, and stress and strain curves on the specimen.

SHPB is widely used in rock dynamics. Li et al. [122–124] developed a modified split Hopkinson pressure bar for a coupling load experiment at medium-to-high strain rate. Zhou et al. [125] gave reasonable predictions for constitutive relationships of rock at different strain rates, which widened the application scope of SHPB. Besides, they investigated the stress evolution and cross-sectional stress uniformity along the thick bar, giving practicable guidance for SHPB test [126]. Gong et al. [127, 128] studied the dynamic characteristics and failure modes of rocks, providing guidance for deep mining. Li et al. [129] analyzed and experimentally studied the problem of normal propagation of longitudinal waves in filled rock joints. The split-Hopkinson pressure bar is shown in Figure 5.

3.3. True-Triaxial Rockburst Test. The true-triaxial test can perform stress and strain studies on the *XYZ* in three directions. If the dynamic load is changed in one direction, the rock sample can be subjected to a dynamic failure test. The systems consisted of true three-axis impact testing machines, linear variable differential transformers, high-speed cameras, digital cameras, and acoustic emission systems. Experiments applied dynamic loads in the *X* and *Z* directions, which can be applied by two independent dynamic loaders, with adjustable amplitude, duration, and frequency to input different stress waves. China University of Mining and Technology, Beijing, Central South University, and Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Northeastern University, and Guangxi University developed true-triaxial rockburst test systems. He et al. [130] applied the true triaxial experiment combined with acoustic emission to obtain the dynamic damage process and characteristics of limestone. Du et al. [131] explored the failure behavior of different rock types using a novel test system coupled to true triaxial static loads and local dynamic disturbance. Feng [132] summed up the research

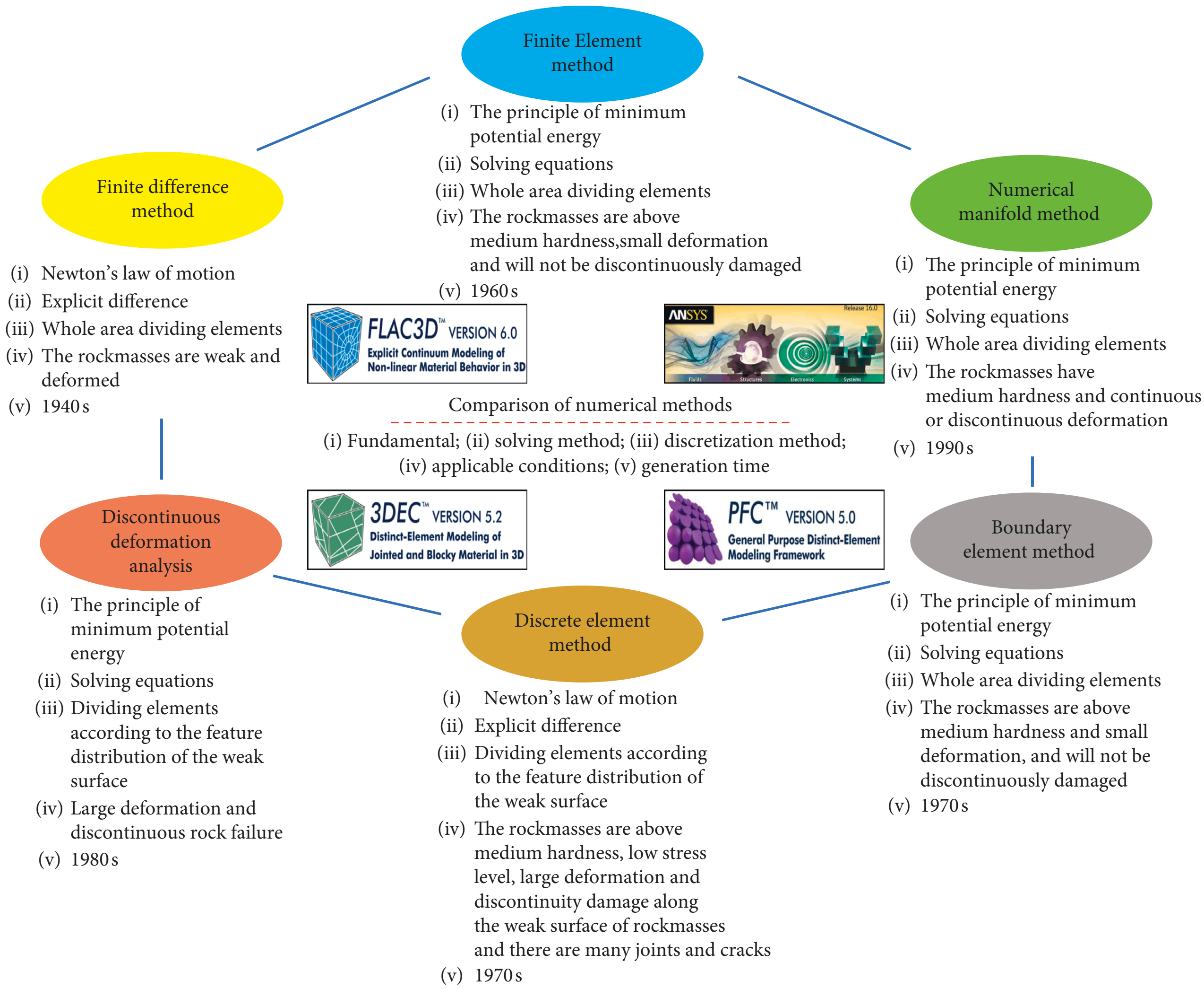

Figure 4: Comparison of several numerical simulation methods (revised from [107]).

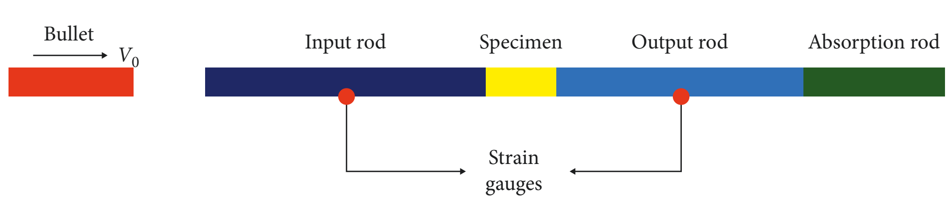

Figure 5: Split-Hopkinson pressure bar diagram.

status of rockburst and mentioned that the true-triaxial test has been developed to study the mechanism of rockburst development process. Su et al. [133] used the improved true triaxial test system to study the development law of granite rockburst. True-triaxial rockburst test is shown in Figure 6 [17].

3.4. Dynamic Centrifuge Model Test. The centrifugal model is a method commonly used in engineering by using similar simulations to study physical phenomena to help solve theoretical and design problems. Earthquake dynamic response of rock and soil is a research hotspot of centrifugal model tests. When conducting studies on earthquakes, explosions, etc., the geotechnical model needs to be placed in the centrifugal field and coupled with a certain frequency of vibration. The vibration can be provided by a centrifugal shaker placed on a working basket. Tsinghua University used the geotechnical centrifugal test to generate horizontal seismic waves through a hydraulic servosystem to simulate the dynamic stability of the slope and provided a new method for analyzing the dynamic stability of the slope [134–136].

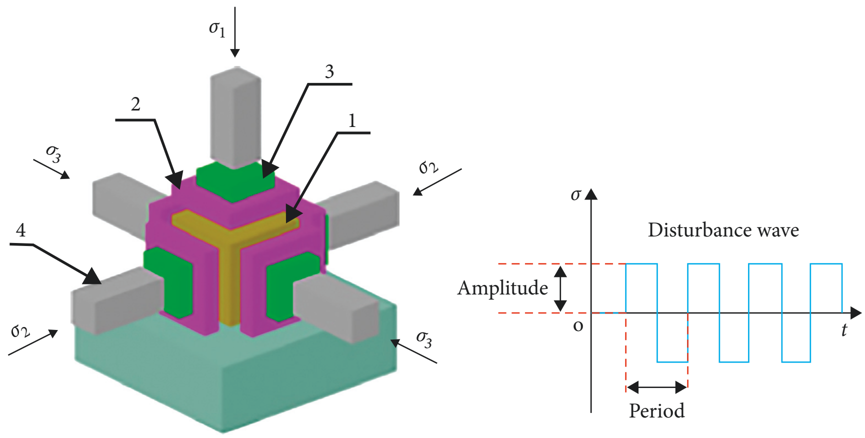

FIGURE 6: True-triaxial rockburst test schematic. (1) Rock specimen; (2) loading platen; (3) sensor; (4) loading bar (revised from [17]).

3.5. Acoustic Emission (AE) Technique. As a result of either dislocations at the microlevel or at the macrolevel by twinning and grain boundary movements, or initiation and propagation of fractures between mineral grains, AE occurs by a crack formed in rocks under high stress. AE is also described as the breaking and destruction of large-area materials on a giant scale or the relative movement between structural elements. When new cracks are created or cracks propagate, the elastic energy stored in the rock suddenly releases. With the occurrence of this process, elastic stress waves are generated and transmitted from the interior of the rock to the boundary, where it is observed as an AE signal [130]. AE technique can effectively monitor the development of microcracks inside the rock until the macroscopic damage process [21, 137]. Indoor AE experiments were widely used in the study of rockmass dynamic damage and achieved certain results [138, 139]. AE technology was also used to monitor coal rock and gas dynamic disasters, as well as slope failure [140, 141]. Moreover, the AE source localization algorithm is constantly improving [142].

3.6. Dynamic Infrared Monitoring. It is used to determine the state of rock, mainly by the infrared thermal imager to observe the distribution and change of infrared radiation temperature during the process of rock loading until its damage [143–145]. Combined with the stress variation curve of the rockmasses, the variation characteristics of the infrared radiation temperature of the rockmasses during the stress process and the impending damage are summarized. The ultimate goal is to use the space-time evolution law of infrared radiation in the process of rockmass to judge, monitor, and predict the stress concentration and damage of rockmass and provide theoretical basis and technology for the early warning of disasters related to rockmass damage. It is important for prediction of rockbursts and earthquakes [146].

Laboratory experiments can obtain the physical and mechanical properties of rock samples and realize the strength of rock under dynamic loading conditions. Compared with numerical simulation methods, it is more intuitive and credible. However, laboratory experiments are costly and cannot be studied for many specific complex conditions. In addition, due to the limitations of the specifications and techniques of experimental instruments, when studying large-scale geotechnical engineering, it is necessary to reduce the proportion of research objects to create similar models, resulting in deviations between experimental results and actual projects. Therefore, in order to overcome these problems, it is necessary to improve the experimental techniques while comparing with the numerical simulation methods to enhance the reliability of the research results.

4. In Situ Tests and Monitoring

4.1. Microseismic (MS) Technique. With the exploitation of deep resources and the utilization of underground space, underground projects continue to develop deeper, and the frequency of rockbursts and other events have greatly increased. Therefore, it is particularly important for the stability monitoring of rockmass. It is an indispensable method to study the dynamic stability of rockmass by analyzing the field data through engineering practice. The MS technique developed based on geophysics can effectively monitor the location of rock microcracks and has been widely used in mines and hydropower projects [147–149]. The location of microfractures obtained through MS technique is used to determine the potential activities of the mine's dynamic disasters and to achieve safety early warning functions [150].

The essence of the MS event is the manifestation of a series of dynamic processes including rock stress-strain and instability damage. Therefore, the MS signal contains a lot of useful information on rock failure and geological defect activation process. The MS technique is widely used in geotechnical engineering, including rockbursts, rockmass collapses, and many other aspects [151]. Enough sensors are placed in the underground space to form a spatial network structure. The sensor network can monitor the stress wave signal emitted during the internal destruction of the rockmass. After filtering, P-wave (S-wave) pick-up, source location, and focal mechanism analysis, the spatial-temporal characteristics of MS events are determined, and quantitative mechanical properties of rockmass are described by quantitative seismological methods. Thereby, the stability of rockmass is analyzed.

The research directions of MS technique are mainly in four aspects: localization, identification, focal mechanism, and early warning.

First, for localization, many various advanced source localization algorithms have been proposed, such as the simplex method, genetic algorithm, and double-difference localization method. Ge [152, 153] summarized the current main iterative methods and analytical methods. Feng et al. [154, 155] introduced an efficient global-optimization algorithm and particle swarm optimization to improve localization accuracy. Li et al. [156] developed a nonlinear MS source localization method using the simplex method, which can search the MS source directly in the error space through four deformations of the simplex figures. However, the accuracy of localization methods based on the arrival time difference is usually affected by the premeasured wave velocity, the iterative algorithm, and the initial value.

To reduce the effects of abnormal arrivals, Dong et al. [157–161] proposed the analytical solution without the need to determine the wave velocity. Figure 7 shows the application of MS localization method without prior velocity measurement in mine. Explicit formulas were developed to resolve the accurate analytical solutions for cuboid and cube sensor networks to avoid the iterative error [147, 162, 163]. However, the geometric shapes of monitoring networks can hardly be special in the practical layout. To solve the above problems, the three-dimensional comprehensive analytical solutions (TDCAS) without premeasured velocity under random sensor networks was proposed [164]. Then, a collaborative localization method using analytical and iterative solutions (CLMAI) was proposed, which combined with the arrivals of multisensor and inversion of the real-time average wave velocity to seek the optimal locating results [165]. The analytical localization method is used to remove abnormal arrivals since it has a stable solution with the high precision when the input data are accurate. The iterative solution without the need of premeasured P-wave velocity is used to improve the locating accuracy since it can optimize results using the advantage of multiple sensors. This method not only eliminates the influence of premeasured wave velocity on localization but also eliminates the influence of abnormal arrivals. Figure 8 shows the application scatter diagram of P-wave velocity solved by the CLMAI method of the mining area for Yongshaba mine.

Secondly, the identification of MS signals is the analysis of P-wave and S-wave arrival times, wavefield characteristics, and signal denoising. The monitored MS signal was identified as the rock fracture signal, drilling signal, electrical signal, heavy vehicle passing signal, and blast signal [166]. Besides, based on large amounts of data and statistical methods, blasts and seismic events were identified. Dong et al. [148, 149] and Zhao et al. [167] used the Fisher Classifier, Naive Bayesian Classifier, and logistic regression to establish discriminators. Databases from three Australian and Canadian mines were established for training, calibrating, and testing the discriminant models. The classification

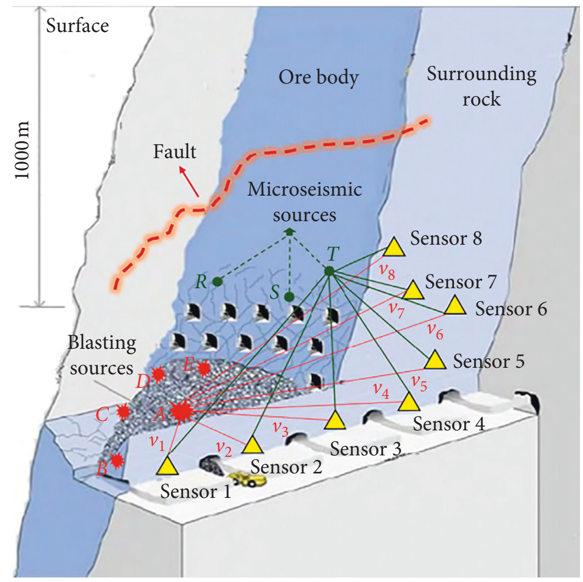

Figure 7: Propagation paths of P-wave with blasting sources and microseismic sources located at different coordinates. In the traditional methods such as STT and STD methods, the average velocity value of blasting source A is equal to the average value of v1 to v8, which is calculated through their own distances and travel times. However, the average velocity values of other blasting sources B, C, D, and E will not equal the source A due to the anisotropy of rock. Similarly, the authentic velocity value of a microseismic source is not equal to the velocity value used in the localization process. Thus, they are inaccurate locating sources using the premeasured average velocity value of the blasting sources, where the velocity paths are different from the sources to be located [164].

performances and discriminant precision of the three statistical techniques were discussed and compared. The proposed discriminators have explicit and simple functions which can be easily used by workers in mines or researchers.

Thirdly, the focal mechanism refers to the physical and mechanical process of MS [168]. MS focal mechanism models are mainly divided into fault models [169, 170], expansion models [171–173], and force-couple models [174]. Moment tensor analysis was performed on the monitored MS information to understand the differences in the gestation mechanism of the strain type and strain-structure-slip type 2 rockbursts in the instantaneous rockburst [175]. Ma et al. [176] fully used waveform inversion and statistical methods to investigate the different MS source mechanisms in a more quantitative way. The caving and moving laws were analyzed to the overlying rock in the repetitive mining, the structure of the key blocks in heavy rock formations, the stress conditions in different regions, and the characteristics of fracture instability. Besides, the mechanism of the mine shock caused by repeated mining was obtained [177].

Finally, the MS warning is to analyze the time and probability of occurrence of MS events and provide guidance for safe construction. Using the cloud computing and Internet of Things, Dong et al. [178] established a prealarm model for tailing the dam based on real-time monitoring and numerical

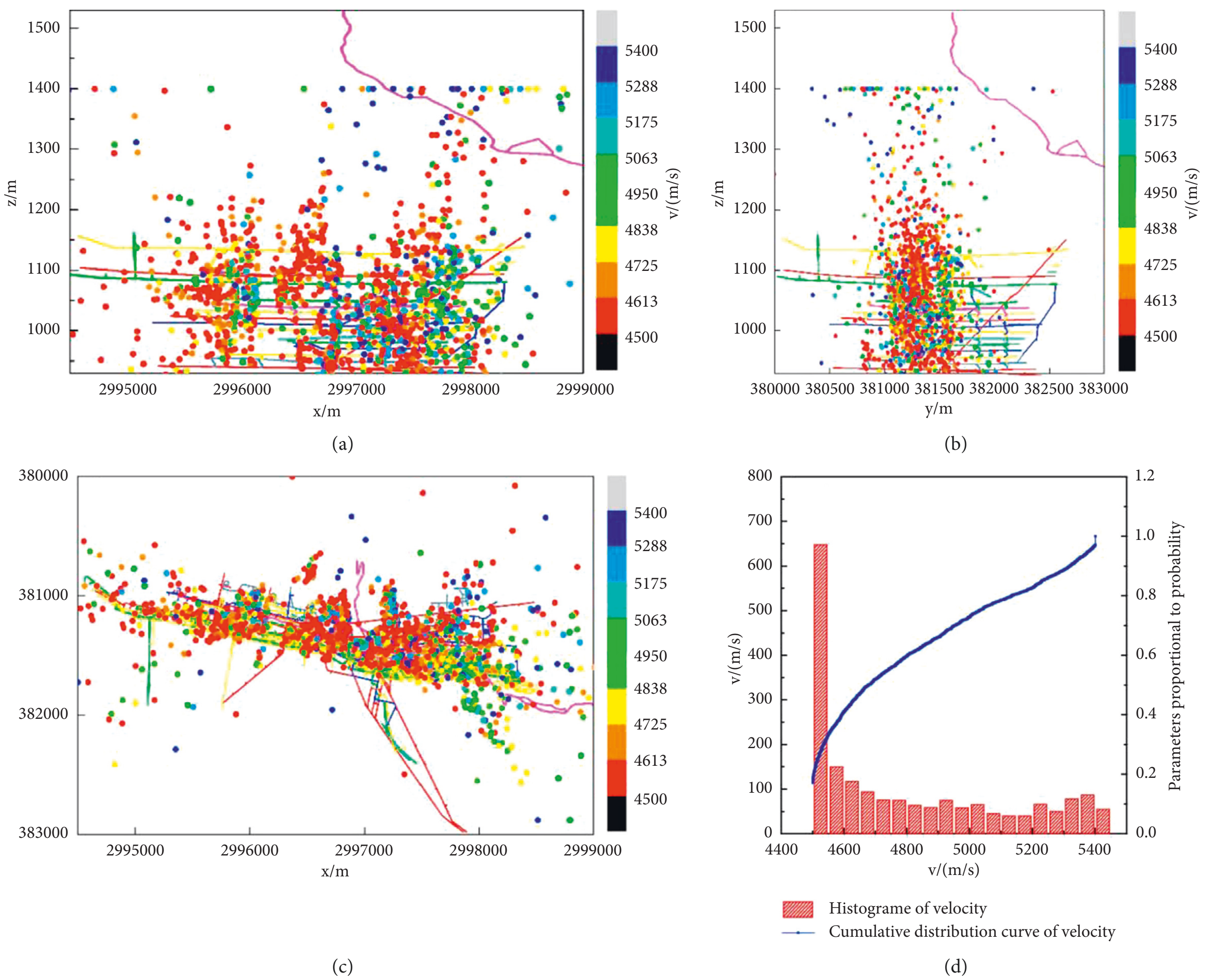

Figure 8: (a–c) Velocity structures of three cross sections. (d) The distribution of velocity for the 1891 events, where the red parts represent the histogram of velocity and the blue curve represents the cumulative distribution curve of velocity [165].

simulation. Combined with the trend of real-time monitoring deformation, as well as calculated dynamic safety factor, random reliability, and interval nonprobabilistic reliability, the stable or dangerous warning signals of the tailings dam can be obtained by the remote real-time prealarm system. By using MS technique, the occurrence of rockbursts was predicted in deep tunnel TBM excavation [179]. According to the measured evolution rules of MS information, Feng et al. [180] used the early warning of rockburst grades to conduct feedback analysis and dynamic control to avoid rockbursts, reduce the level, or delay the time of rockbursts. Taking into account the temporal and spatial characteristics of the seismic sequence before the large magnitude seismic events, Dong et al. [181] used the Gutenberg–Richter magnitude-frequency relationship, Hurst exponent, and Benioff strain to reveal the characteristics of the precursor seismicity. The MS warning technique can be more widely used in the field of rockmass dynamics.

The MS technique method is increasingly becoming one of the mainstream methods for in situ stability monitoring of geotechnical engineering. Numerical simulation and MS are combined to make the research more fully validated [182, 183]. The study of rockmass reliability considering MS loads also provides a new idea for rockmass stability analysis [184]. However, due to the anisotropy of rockmasses, the attenuation of wave velocity propagation in rockmasses and other theoretical studies are still not mature enough, making the monitoring results often have some errors. In addition, the MS technique costs a lot, requires a lot of manpower and material resources for installation and maintenance, and has certain requirements for the performance of the computer. However, with the development of advanced technologies such as artificial intelligence and cloud computing, these problems can be greatly improved.

4.2. Velocity Tomography. As a new geophysical method, velocity tomography, based on the MS technique, has broad application prospects in the field of rockmass dynamics [185]. This technique relies on seismic waves, specifically p-waves, through rockmasses. Velocity tomography can be divided into two types: "active" and "passive." Active sources are generally artificially activated, including explosives, hammers strikes, and vibrations generated by shearer. Passive sources are generally naturally occurring seismic events [186]. The technique involves the forward algorithm and the inversion algorithm. Forward algorithm is used to accurately determine the propagation path of seismic waves, which is a key link in seismic tomography. According to the ray travel path obtained by the ray travel time and the forward algorithm, the wave velocity distribution in the medium is reversed, which is called the inversion algorithm [187].

Velocity tomography has the characteristics of large amount of information and high resolution, so it is widely used in engineering fields. The potential of rockburst in a longwall coal mine was studied by using passive seismic velocity tomography [188]. The three-dimensional velocity tomography technique was used to image the stress redistribution around the longwall of the coal seam to better understand the mechanism of rockburst. It was indicated that velocity tomography was an appropriate technique for monitoring the redistribution of stress in the underground mines [189]. Using the MS events and the arrival time data of the blasting, the P-wave tomogram of the Yongshaba deposit in the underground mining area of Guizhou Province, China, was inferred [190].

4.3. Stress-Strain Monitoring. The stress-strain change of rockmass during the construction process is a very complicated process. It is affected by factors such as the nature of rockmass and the order of excavation. By applying the stress-strain monitoring technique, engineers and technicians can fully grasp the ground pressure state caused by blasting, excavation, etc., so as to ensure the safety of construction and production.

The instrument system used to monitor the stress or strain of the rockmasses is generally composed of three parts: (1) sensors, which can transform the sensed measurement information into electrical signals or other identifiable signals according to certain rules; (2) transmission systems, which can transmit the signals emitted by sensors to the reading systems; (3) reading systems, which convert data into applicable forms for calculation and analysis [191].

The basic principle of stress-strain monitoring is that the surrounding rockmass stresses act on the sensors, stimulating sensors to generate identifiable signals. By the transmission systems, the signals are transmitted or amplified directly to the reading systems. By intermittently or continuously recording the signals, the stress or strain of the rockmasses around the measuring points can be obtained [191].

Stress-strain monitoring is widely used in engineering sites. The Institute of Geology of the Chinese Academy of Sciences (IGN) collaborated with Kumamoto University in Japan to design an improved method known as the compact conical ended borehole overcoring method (CCBO) for determining the stress state of the rockmasses [192]. In addition, the in situ dynamic monitoring technology was used to monitor the stress and strain of the Nantun Coal Mine, which helped to determine the maximum depth of the fracture zone under the coal seam and the width of the significant stress-increasing phase. It was an important factor in controlling mine water inrush [193]. Furthermore, the resistance strain gauge was used to monitor the surrounding rock strain and analyze the failure mode of the specimen, so as to study the secondary stress distribution characteristics and failure mechanism of the tunnel [194]. The stress-strain monitoring technique is constantly improving, which is also an important technology for rock laboratory experiments [195].

4.4. Electromagnetic Radiation Monitoring. The study of electromagnetic radiation monitoring in rockmass damage provides new methods and means for understanding the process, mechanism, monitoring, and forecasting of rockmass dynamic disaster occurrence and development.

A phenomenon in which the heterogeneous bodies, such as coal or rock, radiate energy outward during loading is called electromagnetic radiation. It is formed by the displacement motion of charged particles. It occurs in the process of charge migration and crack propagation caused by displacement deformation of various parts of the heterogeneous bodies. The electromagnetic radiation intensity mainly reflects the loading degree and deformation failure strength of the rockmasses [196]. When an abnormality occurs in the level of electromagnetic radiation monitoring, such as sudden increase, gradual increase, or strong fluctuation, it indicates the occurrence of rockburst. Also, the electromagnetic radiation monitoring value typically exceeds the warning threshold when the rockburst occurs.

This technique is mainly used to monitor and forecast accidents such as mine coal and rock dynamic disasters. Wang et al. [197] developed the KBD5 electromagnetic radiation monitor for coal and gas outburst. Electromagnetic radiation technology was widely used in the prediction of coal and gas outburst and impact ground pressure disasters, roof stability monitoring in goafs, surrounding rock stress distribution and mine pressure observation, and determination of the width of the pressure relief belt [198–200]. Song et al. [201] studied the electromagnetic radiation characteristics of coal-rock samples under uniaxial loading. It has a great theoretical and practical value for using electromagnetic radiation technology to evaluate the mechanical state of coal and rock, as well as accurately monitoring and predicting coal-rock dynamic disasters.

5. Some Comprehensive Analysis Methods Based on Statistical Theories

After a large number of literature statistics and analysis, in addition to the commonly used numerical simulation, experimental methods, and in situ tests, some effective methods have been developed for rockmass dynamic stability problems. Most of these methods are based on a large number of statistical data. Through the collection of geology, rockmasses properties and other related data, models can be established, with applying statistical methods to find the laws, which guide to solve the practical problems.

A three-dimensional Earth model of heterogeneous geomechanics was established in combination with physical and mechanical properties of rockmass and geological survey data. The variations of longitudinal wave velocity and shear velocity in each layer of reservoir rock were taken into account during modeling [202]. Rockbursts are often caused by the superposition of static and dynamic loads. During underground activities, the accumulated elastic energy is suddenly released in the rockmasses, causing failure with a sudden. By using random forest, support vector machine, and naive Bayes classification, Dong et al. obtained nonlinear methodologies for identifying the seismic event and nuclear explosion [203]. Figure 9 shows the application of ROC curves to compare the discrimination performance of different methods. Bayesian networks were used to be able to deal with the characteristics of incomplete data to predict rockbursts [204]. Quantitative statistical analysis was conducted through a large number of geological survey data and seismic data [205]. Adoko et al. [206] used fuzzy inference system (FIS), adaptive neurofuzzy inference systems (ANFIS), and field measurements data to predict rockburst intensity. He et al. [207] applied data mining (DM) techniques to the database to develop predictive models for the rockburst maximum stress and rockburst risk index that required the determination of the test results. Feng et al. [208] comprehensively studied the evolution process of different types of rockbursts in deep tunnels using a large number of indoor and field tests data. Liu et al. [209] proposed a microseismic method for early warning the occurrence probability of rockburst risk. Zhao et al. [210] applied microseismic monitoring data to comparatively study the microseismic characteristics and rockburst risk of deep tunnel excavated by TBM-drilling and blasting method. Feng et al. [211] proposed a fractal calculation method to study the self-similarity of the energy distribution of microseismic events during the development of immediate rockbursts. These methods are effective and have a great reference value for the study of rockmass dynamic stability.

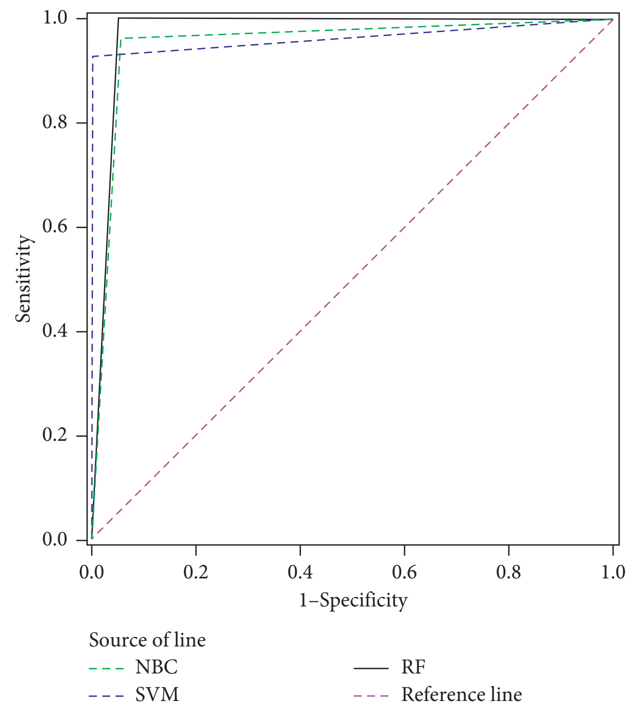

Figure 9: ROC of established RF, SVM (RBF), SVM (liner), and NBC models. The maximum area indicates the best predictive power [203].

6. Conclusions

It is obviously that numerical simulation, laboratory experiments, and in situ tests have wide applications in the dynamic stability analysis of rockmass. In addition, some comprehensive methods based on statistical theories have also been applied. However, there are corresponding deficiencies in different research methods, which require to be continuously improved.

(1) According to the current development of the methods and the stability of rockmass dynamics, FEM, DEM, and FDM are commonly used. Some advantages, including low costs, wide range of applications, and simple using conditions, make the numerical simulation methods widely used. However, because the models are simplified, numerical simulation methods have problems such as lack of intuitiveness, which affect the results.

(2) Laboratory experiments are various. At present, the split-Hopkinson pressure bar test, true-triaxial rockburst test, etc. are used to analyze the dynamic stability of the rockmasses. Laboratory experiments are more practical, reliable, and intuitive. However, the methods require the use of large-scale testing machines. The costs of the experiments are high, and the analyses are limited to certain rock samples.

(3) In situ tests are most suitable for engineering practice, and the obtained data best meet engineering issues. However, these methods require the installation of sensors and other equipment, which have high costs and take long time. In addition, the relevant personnels need to be supervised, and the implementation is difficult.

(4) Some comprehensive analysis methods based on statistical theories utilize a large amount of statistical data, so that they have a certain representation. They can find common rules in a large number of data. It is of great significance to study the natural laws of dynamic stability of rockmass. However, this work requires a lot of time to find data, and it can hardly cover all different situations. The obtained conclusions are not reliable.

(5) There are many uncertainties under the influence of seismic loads including earthquakes, explosions, and rockbursts. In addition, the influence of geological

structures, groundwater, etc. cannot be ignored in considering the stability of rockmass. These problems must be paid more attention in the process of studying the stability of rockmass dynamics.

(6) It has a certain gap to the demand for solutions to many rockmass dynamic problems represented by earthquakes, explosions, and rockbursts, that the dynamic stability analysis of rockmass lacks perfect theories and methods. Therefore, in order to effectively solve the problems of the dynamic stability of rockmass that are becoming more noticeable, we should conduct more in-depth research on the theories and methods of analyzing problems in this field. It is important to note that when analyzing dynamic factors, it is recommended to consider uncertain information.

(7) Through a large number of literatures, it is found that the traditional rockmass dynamic stability analysis methods are more suitable for studying earthquakes and explosions. Due to the difficulty of predicting rockbursts, numerical simulation methods have rarely studied rockbursts. The research methods for rockbursts are mainly MS technique and statistical data analysis. It is urgent to strengthen theoretical research and develop software suitable for rockburst analysis.

Numerical simulation software, laboratory experiments equipment, and in situ tests technique should be constantly improved to more accurately analyze the stability of rockmass under dynamic disturbances. Besides, a set of general comprehensive theories should be completely established to solve the errors caused by different methods. Furthermore, the most effective way to explore comprehensive analysis methods is to integrate the methods, including theoretical analysis, numerical methods, laboratory experiments, and in situ tests, so that they can adapt to different engineering problems and cross-validate each other.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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