Failure Behavior and Seismic Response of Fractured Rock Mass
不連続性岩盤の破壊挙動と地震応答特性の評価に関する研究

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Design and assessment of rock-based structures such as dams, bridges and nuclear power plants require a comprehensive understanding of the deformation, failure and seismic behavior of rock masses involved in constructions. The failure behavior and seismic response of rock masses, which concern the safety and stability of engineering structures to a great extent, are principally governed by the fractures that exist ubiquitously in rock masses, such as cracks, joints and faults. Growth and coalescence of fractures due to the increased external loads can induce the stress redistribution and localized stress concentration, subsequently leading to the failure of rock masses that is usually accompanied by large nonlinear deformations. Additionally, the presence of fractures also affects the propagation of seismic waves in rock masses, due to the occurrence of wave scattering mainly in the form of wave reflection and transmission. The wave scattering changes the propagation directions and amplitudes of seismic waves, and thus affects greatly the seismic response characteristics of rock masses. At present, the failure behavior and seismic response of the fractured rock masses remain as two fundamental and promising issues in rock mechanics and engineering, and thereby need to be studied.

The first part of this thesis focuses on the failure behavior of the fractured rock masses under compression and tension, respectively. An expanded distinct element method (EDEM) with the capability of simulating the cracking process of rock mass was further developed by implanting the tensile-shear failure criterion and Griffith failure criterion into the conventional distinct element method (DEM). Then the EDEM was utilized to investigate the growth mechanism and growth pattern of 2-D cracks in a rock-like material under uniaxial compression, as well as the mechanical and failure behavior of a fractured rock sample under confined compression. Through comparing the results of EDEM simulations with the results of experiments, the validity and accuracy of the EDEM were verified. Due to that the crack growth caused by tensile stresses is more likely to induce the catastrophic rock failure, the growth mechanism of 3-D internal cracks in rocks under tension was also investigated by carrying out uniaxial tension experiments on pre-cracked rock-like samples and the related numerical simulations by using the boundary element method (BEM) code of FRANC3D. In the experimental studies, the effects of geometrical

characteristics of 3-D cracks (including crack dip angle, crack spacing and crack intensity) on the tensile strength and failure modes of samples were examined. To obtain more information of the spatial crack growth under tension, the distribution of mixed-mode stress intensity factors (*SIF*s) and energy release rates (*ERR*s) along the fronts of cracks was studied, and the propagation and coalescence processes of 3-D cracks were numerically simulated.

In the second part of this thesis, a series of theoretical, experimental and numerical studies were carried out to investigate the effects of rock fractures on the propagation of seismic waves as well as the seismic behavior of fractured rock masses. In the theoretical studies, the analytical models considering that different types of simple harmonic waves (including P-wave, S_H-wave and S_V-wave) propagate across an inclined rock joint were formulated on the basis of the displacement discontinuity method. To obtain an insight into the seismic response of the rock joint, parametric studies that take the incidences of P-wave and S_H-wave as examples were carried out based on those analytical models. In the parametric studies, the reflection and transmission coefficients of seismic waves, which represent the amplitudes of the reflected and transmitted waves, were calculated, and their variation tendencies with the properties of joint and incident wave (including joint dip angle, joint stiffness and wave frequency) were analyzed. Additionally, the overall seismic motions of the rock mass at both sides of joint, which can provide important references to the seismic design of rock-based structures, were also investigated and discussed. Then dynamic centrifuge tests on rock-like models with pre-existing joints were carried out to investigate the seismic responses of fractured rock foundations to horizontal shear waves (S_V-waves). Before tests, a servo-controlled vibration apparatus that is composed of an electrohydraulic shaking table and a laminar model container was developed to excite seismic waves and to simulate reliable dynamic boundary conditions for models. During the dynamic centrifuge tests, the effects of joint dip angle and joint intensity on the seismic responses of rock foundation were examined, and the effects of wave amplitude and wave frequency were also taken into account. Finally, numerical simulations based on the dynamic finite element method (FEM) and distinct element method (DEM) were performed to investigate the seismic behavior of the rock foundation under a nuclear power plant when subjected to real seismic loading. Through comparing the numerical simulation results, the basic differences between the FEM and DEM in dynamic simulations were illuminated. Then the FEM and DEM were adopted to examine the seismic responses of rock foundation containing two sets of perpendicularly-distributed joints, and the effects of joint dip angle of the persistent joint set on the overall seismic behavior of rock foundation were investigated.