全球变化与地球系统科学系列

Series in Global Change and Earth System Science

GCESS

Rock Anisotropy, Fracture and Earthquake Assessment

岩体各向异性、动态破裂与地震评估

Yong-Gang Li (Ed.)

高等教育出版社

全球变化与地球系统科学系列
Series in Global Change and Earth System Science

Rock Anisotropy, Fracture and Earthquake Assessment

岩体各向异性、动态破裂与地震评估

Yong-Gang Li (Ed.)

YANTI GEXIANG YIXING DONGTAI POLIE YU DIZHEN PINGGU

高等教育出版社·北京

图书在版编目（CIP）数据

岩体各向异性、动态破裂与地震评估 = Rock Anisotropy, Fracture and Earthquake Assessment: 英文 / 郦永刚主编 .— 北京 : 高等教育出版社，2016. 2

ISBN 978-7-04-044345-5

Ⅰ. ①岩… Ⅱ. ①郦… Ⅲ. ①岩体 – 各向异性 – 研究 – 英文②岩石破裂 – 动态分析 – 英文③岩体 – 地震 – 评估 – 研究 – 英文 Ⅳ. ① P583

中国版本图书馆 CIP 数据核字（2015）第 286745 号

策划编辑	关 焱	责任编辑	关 焱	封面设计	张 楠	版式设计	于 婕
插图绘制	杜晓丹	责任校对	窦丽娜	责任印制	毛斯璐		

出版发行	高等教育出版社	咨询电话	400-810-0598
社 址	北京市西城区德外大街4号	网 址	http://www.hep.edu.cn
邮政编码	100120		http://www.hep.com.cn
印 刷	北京中科印刷有限公司	网上订购	http://www.landraco.com
开 本	787 mm × 1092 mm 1/16		http://www.landraco.com.cn
印 张	18.25		
字 数	380 千字	版 次	2016 年 2 月第 1 版
插 页	8	印 次	2016 年 2 月第 1 次印刷
购书热线	010-58581118	定 价	139.00 元

本书如有缺页、倒页、脱页等质量问题，请到所购图书销售部门联系调换

物 料 号 44345-00

Preface

This book is the third monograph of the earth science specializing in computational, observational and interpretational seismology and geophysics. It contains six chapters to describe: (1) the principle and theory of seismic wave propagation in anisotropic media, shear-wave splitting analysis, the ray series method for inhomogeneous anisotropic fractured rocks; (2) the bonded discrete element method using a new fracture criterion for reproducing the realistic compressive-tensile strength ratio of rocks; (3) rock fracture mechanics in earthquake and its prediction for the earthquake nucleation and stress redistribution ; (4) the multiple linear regression analyses on the relationships between moment magnitude and fault measurements for earthquake hazard assessment; (5) the predictive model of earthquake physics using the pattern informatics algorithm based on statistical mechanics of complex systems; and (6) a fully probabilistic earthquake and tsuinami hazard assessment for Pacific Island Countries with a spatial resolution adequate for local seismic risk studies and building code applications. Each Chapter provides the comprehensive discussion of the state-of-the-art method and technique with their applications in case study. The editor approaches this as a broad interdisciplinary effort, with well-balanced observational, metrological and numerical modeling aspects. Linked with these topics, the book highlights the importance for characterizing the fractured crust that is closely related to earthquake physics.

Researchers and graduate students in geosciences will broaden their horizons about advanced methodology and technique applied in seismology, geophysics and earthquake science. This book can be taken as an expand of previous two books in the series, covers multi-disciplinary topics to allow readers to grasp the various methods and skills used in data processing and analysis as well as numerical modeling for structural, physical and mechanical interpretation of geophysical problem and earthquake phenomena. Readers of this book can make full use of the present knowledge and techniques to understand the fractured crustal rocks and serve the reduction of earthquake disasters.

Contents

Rock Anisotropy, Fracture and Earthquake Assessment

Yong-Gang Li

This book presents disciplines, methods and techniques for defining fractures in the earth crust, the bonded discrete element method using a new fracture criterion, rock fracture mechanics for analyzing the earthquake nucleation and stress redistribution, the multiple linear regression analyses on the relationships between earthquake moment magnitude and fault measurements for hazard assessment, the pattern informatics model based on the statistical mechanics of complex systems for evaluation of earthquake probability, and a fully probabilistic earthquake hazard assessment for local seismic risk studies and building code applications. Authors from global institutions illuminate multi-disciplinary topics with case studies. All topics in this book help further understanding earthquake physics and hazard assessment in global seismogenic regions.

While a large variety of mechanisms may give rise to anisotropy, such as crystal alignment, grain alignment, stress-induced alignment of cracks, and thin sedimentary beds, seismic wave anisotropy is a wide spread phenomenon for fractured rocks in the earth crust. With the increasing resolution of seismic observations using three-component seismometers, rock anisotropy has been widely revealed in the crust and upper mantle. Many observations of seismic anisotropy is related to aligned cracks, since the upper brittle part of the earth crust is pervaded by distribution of cracks which are preferentially aligned by non-lithostatic stress. We are particularly interested in the seismic wave propagation in the anisotropic medium containing aligned cracks because the earthquake process and fluid transport in geothermal and hydrocarbon reservoirs, in nuclear waste repositories and in gas-rich shale sedimentary rocks are closely tied to the presence of fractures, particularly aligned fracture sets in the host rock. The search for fracture related earthquake precursors at crustal depths using seismic methods began since 1970s. Aftermath, shear-wave splitting (SWS) observation in three-component seismograms has been widely used as a direct means to characterize the population of fractures contained in the host rock. Studies of shear-wave propagation through fractured media showed that a small degree of crustal fracture alignment along the wave propagation path would, in principle, induce separation or splitting between shear-waves polarized parallel to faces of the dominant fracture population and shear-waves polarized perpendicular to these fracture faces. Wave polarization anomalies are also found to be sensitive diagnostics of the degree of rock anisotropy, and its symmetry and orientation. In Chapter 1 of this book, we review the principle and theory of seismic wave propagation in an anisotropic medium induced by aligned cracks, introduce the 3-D ray series method with applications for inhomogeneous anisotropic medium, and illustrate observations and modeling of seismic anisotropy in fractured crustal rocks. The method and technique to defining the orientation and density of a population of crustal cracks described in this chapter are helpful for further understanding the damaged structure of fault zones in earth crust and also useful in exploration of geothermal reservoirs and hydro-fracturing shale gas.

It is important to investigate fluid-solid interaction problems in engineering and scientific fields. These problems may include fluidized cracks and beds, liquefaction, particle suspension, fluvial erosion, transportation and sedimentation. One of such interaction problems deals with large deformation, or even fracturing of solids and the flow of fluids in the fractures of solids, for example, in petroleum industry where high pressure fluids are injected into boreholes to fracture reservoir rocks to enhance the flow of gas, oil or other fluids. In geophysical researches, there are interests to study the relations between earthquake occurrence and underground water flow or water injection in reservoirs. In the study of tsunami generation and inundation, there is a strong coupling between the movement of water and solid materials. In these problems, the movement of solid materials is accompanied, influenced or even driven by fluid flow of different forms, and flow patterns are strongly affected by the presence and movements of solids. Therefore the two-way solid and liquid coupling is critical in understanding the behavior of such interactions. For solid-fluid coupling problems, various combinations of models for the particle phase and fluid phase can be made depending on the type of problem. The current study introduced in Chapter 2 of this book is mainly focused on the impact of stiffness and fracture parameters on the macroscopic response. The bonded discrete element methods are used to model rock fracture, the compressive to tensile strength ratio and the internal frictional angle, in terms of a new fracture criterion, which is based not on forces in a single bond but on the average stress of neighboring particles and has the form of macroscopic Mohr-Coulomb criterion with explicit tensile cut-off. Elastic and fracture parameters for random packing of particles are then obtained by numerical simulations. It has been successfully utilized to the study of physical process such as rock fracture, stick-slip friction behavior, granular dynamics, heat-flow paradox, localization phenomena, Load-

Unload Response Ratio (LURR) theory and Critical Point (CP) systems. It is also found in numerical models that the closest packing of particles in 3-D case generates anisotropic elasticity.

Mature faults are planes of weakness in the earth crust. They facilitate slip under the prevailing stress orientation to initiate earthquakes. Extensive field and laboratory research, and numerical simulations indicate that the fault undergoes high, fluctuating stress and pervasive cracking during an earthquake. Quantitative studies of earthquakes based on the fault model in the past decades took kinematic and dynamic approaches. The kinematic approach is basically solving an inverse problem in which we determine the fault slip function in space and time from observed seismic records by means of the elasto-dynamic representation theorem; kinematic model parameters were also interpreted in terms of fracture mechanics. On the other hand, the dynamic approach attempts to predict the fault slip function based on a given distribution of rupture strength over the fault plane and the loading stress condition by means of the principle rupture mechanics. The two approaches are now combined to produce the distribution of stress drop and that of fracture strength over the fault plane. For all these models, knowledge of fracture mechanics is an important tool in improving our understanding of the mechanical performance during fault rupture in an earthquake. It applies the stress and strain on the microscopic crystallographic defects in real rocks to predict the macroscopic mechanical failure of the rock. The prediction of crack growth is a main task of the damage tolerance discipline. In Chapter 3 of this book, the propagation of cracks in rock materials during an earthquake is studied in detail. Fracture mechanics is introduced to earthquake and becomes an effective method in analyzing the earthquake development and nucleation and redistribution of stress induced by an earthquake.

Other three Chapters (4, 5 and 6) of this book focus on the newly developed methods and technique for forecast and assessment of earthquakes in the fractured earth crust. Estimating maximum magnitudes of future earthquakes in a particular region is extremely important for evaluating potential earthquake hazard, as well as for disaster prevention and reduction. The relations between earthquake magnitude and observed fault measurements (the surface rupture length, subsurface rupture length, rupture width, rupture area, maximum displacement at surface and average displacement at depth) have been carefully analyzed using simple linear regression. However, there still remain issues unsolved, such as how many and which predictors are necessary for improving the estimation of the earthquake magnitude. A more reliable multiple linear regression analyses on the relationships between magnitude and fault measurements are presented in Chapter 4.

Suffering from intense earthquake disasters, seismological community has being promoted the study of earthquake forecast and developed forecast schemes. The pattern informatics (PI) algorithm, a predictive algorithm for the analysis of seismic activity based on the statistical physics of complex systems, has been successfully applied to many seismogenic regions. The PI algorithm assumes that seismogenic dynamics can be regarded as a 'threshold system' driven by persistent forces or currents. By analyzing the fluctuations of seismicity, the PI algorithm estimates the increase of the probability of earthquakes at an intermediate-term time scale. Chapter 5 summarizes the results of this innovative method applied for seismogenic regions of Sichuan-Yunnan in China and Andaman-Sumatra in Indonesia.

One component of the main objective for earthquake hazard assessment is to create a uniform and detailed regional seismic hazard model that captures the spatial variation of the hazard and could be used to support realistic estimation of the earthquake ground shaking risk across the region. A fully probabilistic earthquake hazard assessment carried out for fifteen Pacific Island Countries (PICs) is presented in Chapter 6. Based on historical and instrumental earthquake catalogs, subduction zone segmentation and plate motion information, geodetic data, and available data on crustal faults, a regional seismicity model was built by using different ground motion prediction equations for different types of earthquakes. Then the seismic hazard maps are developed and tested with a spatial resolution adequate for local seismic risk studies and building code applications. This study also includes modeling of earthquake-induced tsunami hazard.

This book includes six Chapters. They are introduced as below.

Chapter 1: "Seismic Wave Propagation in Anisotropic Rocks with Applications to Defining Fractures in Earth Crust" by Yong-Gang Li.

In this Chapter, the author reviews explicit formulas derived from different elastic wave propagation theories and used in direct calculation of wave velocities in anisotropic medium, and introduces the ray theory for anisotropic media and the 3-D ray tracing system of equations applicable to the heterogeneous crack-induced anisotropic media. The most general form of rock anisotropy with 21 independent elastic constants is discussed. In this case, the Christoffel matrix is a 3×3 symmetric positive-definite matrix formed by elastic parameters and components of slowness vector. It has three real eigenvalues G_m with mutually orthogonal eigenvectors, corresponding to phase velocities and polarization vectors of three types of body-waves, respectively. Using matrix techniques to define elastic anisotropy of rocks containing aligned cracks greatly simplifies the analysis of anisotropic features of seismic wave propagation. In the computer procedure, only a subroutine is required to rotate the elastic tensor into the desired configuration while the main program remains independent of direction of wave propagation and type of anisotropy symmetry system. If there are two or more sets of cracks aligned in different directions, we can obtain the overall correction of elastic constants by calculating for each set and then adding them together.

Velocities of body waves propagating in an anisotropic medium can be obtained from Kelvin-Christoffel equations and its characteristic equation associated with the Christoffel tensor. The computation of reflection and transmission coefficients at an interface between two anisotropic media is determined using a numerical technique called slowness surface method. The ray tracing system of equations applicable either to the isotropic or anisotropic medium is introduced. The ray tracing algorithm with inverse for computation of traveltimes and vector ray amplitudes in layered inhomogeneous anisotropic media is then developed and used for interpretation of the fracture structures in 3-D using the VSP data recorded across the fault zone associated with the $M5.7$ earthquake at Oroville in Northern California and near the San Andreas fault at Hi Vista of Mojave Desert, and the data recorded at the seismic network in Los Angeles Basin in Southern California. Results from these investigations show that the Červený ray theoretic traveltime and amplitude computation is an accurate and robust technique for investigating the properties of low to moderate anisotropic and heterogeneous crustal rocks as well as the stress status in the region.

Chapter 2: "Reproducing the Realistic Compressive-tensile Strength Ratio of Rocks using Discrete Element Model" by Yucang Wang and William W. Guo.

Authors of this Chapter present the bonded discrete element methods used to model rock fracture, the compressive to tensile strength ratio and the internal frictional angle, in terms of a new fracture criterion with tensile cut-off. To overcome the difficulties in conventional DEM model, the new criterion based on averaging the stresses of a group of particles has been proposed: if the average stress of two particles satisfies the truncated Mohr-Coulomb criterion, the bond between particles can break. The new criterion is not based on forces in a single bond, but based on the stress obtained by averaging the stresses in the neighbor particles surrounding the particle in question. The results show that the new failure criterion leads to a better agreement with the known experimental results.

In this Chapter, authors give a brief introduction to the ESyS-Particle, an open source DEM software developed at the University of Queensland, Australia. It was designed to provide a basis to study the physics of rocks and the nonlinear dynamics of earthquakes. The ESyS-Particle includes three fracture parameters: particle scale tensile strength, particle scale friction angle and tensile cut-off ratio. The major features that distinguish the ESyS-Particle from existing DEMs are the explicit representation of particle orientations using unit quaternion, complete interactions (six kinds of independent relative movements are transmitted between two 3-D interacting particles) and a new way of decomposing the relative rotations between two rigid bodies such that the torques and forces caused by such relative rotations can be uniquely determined. The current study is mainly focused on the impact of stiffness and fracture parameters on the macroscopic response. Once the samples are generated, uni-axial compressive tests are carried out to calculate the unconfined compressive strength, and the Brazilian and direct tensile tests are performed to evaluate the tensile strength. Elastic and fracture parameters for random packing of particles are then obtained by numerical simulations. The ESyS-Particle has been successfully utilized in study of physical process such as rock fracture, stick-slip friction behavior, granular dynamics, heat-flow paradox, localization phenomena, Load-Unload Response Ratio theory and Critical Point systems. It is also found in numerical models that the closest packing of particles in 3-D case generates anisotropic elasticity. For example, Face-Centered Cubic (FCC) lattice yields cubic elasticity, the simplest case for an orthotropic solid. Based on this research, the particle scale stiffness can be easily calibrated according to the given Young's modulus and Poisson ratio in the case of regular packing.

Chapter 3: "Rock Fracture under Static and Dynamic Stress" by Jiming Kang, Zheming Zhu, and Po Chen.

This chapter presents the application of rock fracture mechanics in earthquake and its failure prediction. At first, a general theory is given, such as the three kinds of crack modes, the stress field near the crack tip and energy release rate, etc. Then, Authors introduce some recent applications of rock fracture mechanics and discuss some challenging issues. Because the stress distribution in the earth crust is complicated, it is still hard to get a whole picture of the energy distribution in an earthquake. Authors use the J-integral, a way to calculate the strain energy release rate, or work energy per unit fracture surface area, in the material.The J-integral is equal to the strain energy release rate for a crack in the rock subjected to monotonic loading. This is generally true only for linear elastic materials under quasi-static conditions. For rocks that experience small-scale yielding at the crack tip, J can be used to compute the energy release rate under special circumstances such as monotonic loading in Model III (anti-plane shear). The strain energy release rate can also be computed from J for pure power-law hardening plastic materials that undergo small-scale yielding at the crack tip. The quantity J is path-dependent for monotonic mode I and mode II loading of elastic-plastic materials, so only a contour very close to the crack tip gives the energy release rate. J is path-independent in plastic materials when there is no non-proportional loading that is the reason for the path-dependence for the in-plane loading modes on elastic-plastic materials.

Accordingly, authors provide detailed formulas used in maximum Hoop stress theory, strain energy density theory, crack growth under dynamic loading and dynamic crack propagation in rock. They further discuss the cohesive model in rock fracture, stress change in the slip-weakening model, and the relationship between energy release range and the parameter in slip-weakening model. Finally, the numeric methods for fracture mechanics, such as the singularity element method and extended finite element method, are developed to overcome difficulties in meshing and re-meshing within the crack tip region that contains the stress concentration. Therefore, these methods with fracture mechanics are applicable to understand the causes of failures and also verify the theoretical failure predictions with real earthquake failures.

Chapter 4: "Multiple Linear Regression Analyses on the Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement" by Annie Chu and Jiancang Zhuang.

In this chapter, authors present the multiple linear regression analysis method to explain the relationship between earthquake moment magnitude and fault measurements (the surface rupture length, subsurface rupture length, rupture width, rupture area, maximum displacement at surface and average displacement at surface) reliably. Based on the highly linear correlations between pairs of the variables, the transformation method is applied to the six quantitative regressors, and then fit linear models between moment magnitude and the regressors. Akaike Information Criterion (AIC) is used as a model selection criterion. A model diagnosis is delivered by normal quantile-quantile plots and residual-on-fit plots to verify the assumption that the errors follow normal distribution with mean 0 and constant variance. The normal QQ-plots appear approximately linear, and this phenomenon supports reasonably good fit to the model with no violation of normality. Other tests that they have implemented, such as examining Cook's distance and leverage, show evidences that no outlier raises concerns. Through testing different models, authors show that these factors associated with a fault are neither independent nor equally important when the moment magnitude is estimated. Some of these factors may be eliminated when constructing a multiple linear regression model. The maximum displacement and rupture area provide adequate information to construct a very good model. When the maximum displacement is not available, the rupture surface and rupture width are the two predictors that provide the best model alternatively. Besides the quantitative predictors, their one-way analysis of variance (ANOVA) approach by adopting slip type and direction reveals that these factors are insignificant when predicting moment magnitude possibly due to two reasons: (1) The energy released by earthquakes is more concentrated on the asperity part or the locked part of the faults where the maximum displacement usually occur while the movement on the other part of the fault is more passive; (2) The errors for the estimate of the average displacement are much bigger than the maximum displacement.

Chapter 5: "PI Algorithm Applied to the Sichuan-Yunnan Region: A Statistical Physics Method for Intermediate-term Medium-range Earthquake Forecast in Continental China" by Changsheng Jiang, John B. Rundle, Zhongliang Wu, and Yongxian Zhang.

In the 2nd volume of this book series, Jiang and Wu have demonstrated some of useful tactics in analysis of earthquake catalog data and make notes on the existing methods used for analysis of seismicity, such as the Eclipse method and the Bayesian information criterion (BIC) and the de-clustered Benioff strain method.

They use an 'eclipse method' based on the concept of modern astronomy for analyzing remote planets to screen out the seismicity in the neighboring active fault zones, for example, in analysis of seismicity for the 2008 $M_S8.0$ Wenchuan earthquake catalog data. The BIC consideration provides a useful aid to judge whether the apparent 'accelerating' trend is statistically significant. In this chapter, the authors introduce the pattern informatics (PI) model which is one of the recently developed predictive models of earthquake physics based on the statistical mechanics of complex systems. They demonstrate the retrospective forecast test of the PI model conducted for the earthquakes in Sichuan-Yunnan region and explore the possibility to apply this method to reverse tracing the increasing probability of strong earthquakes. For earthquakes in Sichuan-Yunnan region, they investigated the stability of the PI algorithm against the selection of model parameters. They adjusted the parameters systematically and tested the effect of such parameter variation. As a result, optimizing parameters were selected for the 'target magnitude' of $M_S5.5$: a fifteen-year long 'sliding time window'; the 'anomaly training time window' and 'forecast time window' both being 5 years; the spatial grid taken as $D = 0.2°$ and only shallow earthquakes with depth ranging from 0 to 70 km are considered. Jiang and Wu (2010) also applied the same parameter settings to do retrospective case study for the 2008 Wenchuan $M_S8.0$ earthquake. Results from the ergodicity test for the Sichuan-Yunnan region indicate that the PI algorithm is valid for this region in the time period under consideration. For different grid sizes and different cutoff magnitude values, the ergodicity test shows that the seismicity in Sichuan-Yunnan region has had a strong ergodicity since 1978, and the PI algorithm has been able to be used for the estimation of time-dependent earthquake rates.

Chapter 6: "Probabilistic Seismic Hazard Assessment for Pacific Island Countries" by Y. Rong, J. Park, D. Duggan, M. Mahdyiar, and P. Bazzurro.

In this Chapter, authors present a fully probabilistic earthquake hazard assessment study carried out for fifteen Pacific Island Countries (PICs). A regional seismicity model was built based on historical and instrumental earthquake catalogs, subduction zone segmentation and plate motion information, geodetic data, and available data on crustal faults. They used different ground motion prediction equations to account for different types of earthquakes. The effect of site conditions on ground motion was modeled based on shear wave velocities derived from microzonation studies and high-resolution topographic slope data. A comparison of their findings with those of earlier studies, such as the Globle Seismic Hazard Assessment Program (GSHAP), shows similarities, and in some cases, significant differences. The seismic hazard maps developed here have a spatial resolution that is adequate for local seismic risk studies and building code applications.