岩体爆破的块度理论及其应用

张继春 著

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FRAGMENT-SIZE THEORY OF BLASTING IN ROCK MASS AND ITS APPLICATION

张继春　著

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张继春　著

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内 容 提 要

本书是一部关于岩体爆破的块度理论及其应用方面的专著，全书共分八章。第一章综述了国内外的有关研究现状及其存在的主要问题；第二章提出了节理间距的康托集分布、实现了岩体天然块度计算的蒙特卡洛模拟；第三章讨论了爆破块度与破碎机制的关系；第四章建立了岩体爆破块度的损伤力学模型(BDM)；第五章应用体视学原理提出了测定爆堆块度组成的一种新方法；第六章提出了确定影响岩体爆破质量主要因素的灰关联分析方法；第七章介绍了有关理论的应用实例；第八章对全书进行了总结与展望。

本书可供矿山、水利水电、交通运输等部门从事爆破工程的生产、科研人员及有关院校的师生参考。

前　言

矿岩爆破块度是定量评价爆破质量的重要指标，它影响到矿山各后续生产工序的效率和采矿生产的总成本。在爆破筑坝工程中，爆破块度对坝体质量有决定性影响。因此，对岩体爆破块度进行深入研究具有重大的实际意义。

实际的岩体都是被节理、裂隙等弱面所切割过的，这些弱面对爆破块度起着重要作用。要解决爆破块度问题，必须寻求一种描述节理、裂隙分布的适当方法，以便将节理、裂隙分布引入岩体爆破的物理过程，分析带节理的岩体爆破机制和爆破岩块的形成规律。另一方面，由于爆破块度的测定一般不可能用筛分法，只能从表（断）面所视推论整体。但是，迄今为止，还没有正确利用体视法原理来解决这个问题，只是用一些经验系数来校正测定结果，达不到必要的精度。

本书应用体视学原理，导出了随机测线被岩块截出的诸线段长度同爆堆块度分布之间的关系，给出了测定爆堆块度时的计算新方法——体视概率计算法。在不进行任何校正的情况下，九次同块度级试验的测定误差均值为 8.67%，十次不同级配试验测得的块度组成与筛分值非常接近，各级含量的绝对误差均值不超过 5.26%；而用著名的 Барон 方法测定时，相应的数值分别为 59.21% 和 9.11%。

从分形理论出发，研究了岩体各种节理的分布规律。通过分析实际断层分布、现场实测节理裂隙分布和岩石试件的微裂隙分布特征，证实了岩体的各种断裂几何形状在有限层次上均具有分形结构，用盒维数法可以计算其分维数。辽宁省大石桥—桦子峪地区

的断层分维数为 1.297 3 ～ 1.357 0，桦子峪矿区的节理裂隙分维数为 1.458 2 ～ 1.465 5，说明该区域的断层密度较节理裂隙密度小，桦子峪矿区内的节理裂隙分维数无显著变化。研究结果还表明：在相同的测度变化比例内，同类型断裂的分维数具有相对稳定性；随着断裂规模的减小，分维数有增高趋势；用分维数值可以对不同类型、不同规模的断裂分布进行定量对比分析。

统计分析桦子峪矿区实测节理间距组成发现，节理间距组成具有有限层次的统计自相似性，根据这种特征，用均匀康托集构造，可以再现其分形结构，每一次构造都呈现出同级序节理间距的等距规律，据此，提出了节理间距的康托集分布。这种分布比常用的负指数分布能更准确地描述各间距级内的节理含量，并可以限定间距变化范围，体现了工程岩体具有"尺寸效应"的特点。在节理间距的康托集分布基础上，应用蒙特卡洛模拟原理，给出了计算岩体天然块度组成的方法。

用随机分形的构造模型描述爆破岩块的形成过程，由此推得的块度分布公式与 G-G-S 经验分布式相同，说明了爆破岩块组成的分形结构是这个经验分布的数学基础。同时，还确立了岩体破碎概率 f、分裂相似比 r 与块度分维数 D 之间有着 $f = r^{3-D}$ 的关系。

按照损伤力学的处理方法，着重分析了爆破过程中的节理破裂机制，推得的节理破裂概率计算公式定量地表示了裂隙对节理破裂的影响程度。在此基础上，应用统计方法，建立起节理岩体爆破块度计算的损伤力学模型(BDM)，这个模型沟通了岩体爆破过程与其块度组成的联系，弥补了现有块度模型不能反映节理破裂的不足。

将岩体爆破视为灰色系统加以研究，应用灰关联分析方法确定影响爆破质量的主要因素。计算与分析结果表明：在不同岩体性质、不同爆破条件下，同一种爆破参数对爆破块度的影响程度不同；爆破块度指标主要受岩体节理裂隙分布控制，其中，节理裂隙间距影响着平均块度和特征块度；对爆破块度起主导作用的爆破

参数是最小抵抗线和炮孔间距。

最后，将上述研究方法和成果综合应用于桦子峪镁矿的生产爆破之中，分别统计和测定了十次生产爆破的矿岩节理间距组成、爆破参数和爆破块度。计算与分析结果表明：桦子峪矿区东、西两个采场的小间距节理裂隙含量较大，其间距分维数为 0.709 6 ～ 1.177 4；天然块度组成具有如下规律，即在 F_{50} 以下和 F_{80} 以上与其 R-R 分布吻合较好，F_{50} 与 F_{80} 之间又与其 G-G-S 分布吻合较好；影响爆破块度的主要因素是节理频数、孔距、炸药单耗和抵抗线，生产爆破中，所采用的孔距和抵抗线偏小、炸药单耗偏大是造成爆破块度大和大块率高的主要原因；在节理、裂隙发育的矿岩中爆破，小孔径的爆破效果比大孔径的好。

本书共分为八章：第一章阐述了岩体爆破机理及其块度模型的研究现状、存在的主要问题和今后的研究趋势，介绍了本书的主要工作；第二章应用分形理论研究岩体断裂几何形状的分布特征，提出了节理间距的康托集分布，并在此基础上实现了岩体天然块度计算的蒙特卡洛模拟；第三章采用随机分形构造模型描述爆破岩块的形成过程，指出了建立岩体爆破块度计算模型的正确途径；第四章按照损伤力学的处理方法研究爆破过程中岩体沿节理面破裂的力学机制，建立了岩体爆破块度的损伤力学模型(BDM)；第五章应用体视学原理提出了测定爆堆块度组成的一种新方法，介绍了该方法的基本原理与实验结果；第六章根据爆破块度受多因素控制的特点，提出了确定影响岩体爆破质量(块度)主要因素的灰关联分析方法；第七章将前述岩体爆破块度理论综合应用于桦子峪镁矿的生产爆破之中，对其爆破技术进行分析研究；第八章对全书的研究成果进行了扼要总结，并讨论了进一步研究的主要问题。

笔者在撰写过程中紧紧抓住对岩体爆破块度起主要控制作用的节理裂隙等宏观弱面分布这一关键之点，以实测数据为基础，注重体系的完备、理论推导的严密和技术方法的实用性；层次清晰，逻辑性强；各章自成体系，又相互联系；语言简洁，图文并茂。

本书的主体为笔者在东北大学的博士学位论文，近年来又做了一些修改和补充。在本书的形成和撰写过程中，始终得到了笔者的两位导师——东北大学的徐小荷教授和钮强教授的悉心指导、关心和支持，他们活跃的学术思想、敏锐的洞察力和严谨的治学态度令笔者受益匪浅。在此，谨向两位恩师致以诚挚的感谢和崇高的敬意。西安建筑科技大学的高金石教授、秦明武教授对笔者的研究工作给予了热情的指导和帮助，特向他们致以衷心的感谢。

本书的出版得到了西南交通大学出版基金的资助。

由于岩体爆破过程的瞬时性和复杂性，而且爆破块度研究涉及到爆炸动力学、计算力学、损伤力学以及岩土工程、采矿工程和工程地质等多学科专业的相互交叉，研究难度较大，至今仍有许多问题没有很好解决，加之笔者学识水平和经验有限，书中难免有不妥之处，恳请读者不吝赐教。

张 继 春

1999 年5 月于西南交通大学

PREFACE

The fragment-size distribution from blasting of ore mass and rock mass is an important index to evaluate the blasting quality quantitatively. It affects the efficiency of each follow-up producing process and the total cost in mining. In building dam engineering with blasting, the blasting fragment-size has a principal influence on the dam quality. Therefore, making a thorough study on the fragment-size in rock mass blasting is of momentous practical significance.

The rock mass has been cut by various kinds of weak planes such as joints and cracks which play an important role in the blasting fragment-size. To solve the problem of blasting fragment-size, a suitable method describing the distribution of joints and cracks must be found so as to introduce this distribution to the physical process of rock mass blasting and analyse the blasting mechanism of jointed rock mass and the law of forming rock fragments. On the other hand,because the screen method usually can not be used to measure the blasting fragment-size, the size distribution of the whole muck pile can only be deduced and obtained from the fragment-size distribution of muck pile surface or its section. So far,the stereoscopic theorem has not be correctly applied to solve this problem. The measuring results are merely corrected by empirical coefficients, which can not answer for the necessary precision.

With the application of stereoscopic theorem, the relation between the lengths of fragments cutting the random surveying lines and the fragment-size distribution of a muck pile was deduced in this book. A new calculating method of measuring fragment-size of a muck pile, the stereoscopic probability calculation method, was given. Without any correction, the average value of measuring errors resulting from all the 9 experiments of the same size grade is 8.67%. The size compositions measured from the different size grades are quite close to the corresponding screen values and the average value of the absolute errors of each grade content does not exceed 5.26%. But the corresponding values, measuring wih the famous Барон method, are 59.21% and 9.11% respectively.

Proceeding from fractal theory, the distribution law of various kinds of joints in rock mass was studied. Based on actual fault systems, field joint systems and microcrack nets of rock samples, it was proved that the fractal structures exist in geometry of various kinds of failure rock in a limited order and that the box-counting algorithm can be used to calculate their fractal dimensions. The fractal dimensions of fault systems at Dashiqiao-Huaziyu region in Liaoning province are 1.297 3 ~ 1.357 0 and the fractal dimensions of joints and cracks at Huaziyu mine are 1.458 2 ~ 1.465 5, which shows that the fault density in this region is less than that of joint and crack in the same region and that the fractal dimensions of joint and crack within Huaziyu mine region do not vary obviously. The results from the study also showed that: within the same proportion of measure variety, the fractal dimensions of the same kind of fracture are approximately equable; with the decrease of fracrure scale given in a regin, however, the fractal dimensions increase progressively; the fracture distributions of different type and scale may be quantitatively contrasted and analysed by applying their fractal dimensions.

From the analyses of spacing composition of field joints at Huaziyu mine region, it was found that the composition of joint spacing is of statistical self-similarity in the limited order. In the light of this characteristic, the fractal structure of joint spacing reappears through the construction of uniform Cantor Set. Each construction all presents the equivalent spacing regularity of the same grade joints. Thus, a Cantor Set distribution of joint spacing was advanced, which can describe the joint content of each spacing grade more accurately than the negative exponent distribution and may restrict the scope of joint spacings. This new distribution embodies the dimension effect of engineering rock mass. On the basis of Cantor Set distribution of joint spacing, the method of calculating natural fragment-size was given by Monte-Carlo simulation theorem.

The forming process of blasted fragments was abstractly described by the structure of a random fractal model. The fragment-size distribution deduced from the fractal model is the same in form as the empirical G-G-S distribution. This shows that the fractal structure of blasted fragment is the mathematical fundamental of this empirical distribution. Moreover, the relation among breakage probability f, similar ratio of fracture r and fractal dimension of fragment-size D is also established, that is, $f = r^{3-D}$。

According to the researching method of continuum damage mechanics, the breaking mechanism of joints, in the blasting process, was emphatically analysed. The calculating formula of joint breakage probability was deduced, which guantitatively indicates the influence of crack upon joint breakage. Through statistic method, the damage mechanics model of calculating fragment-size of jointed rock mass blasting (BDM) was established. This model not only bridges the relation between the process of rook mass blasting and its fragment-size, but also makes up the deficiency of existent models which can not reflect joint fracture.

Considering rock blasting as a grey system, the primary factor affecting blasting quality index was easily deterimined by grey correlation analysis. The calculation and analyses showed that: 1) under the condition of different rock quality and different blasting mode, the identical parameter has the different influence upon the blasting fragment-size; 2) the indices of blasting fragment-size are principally controlled by the joint and crack distribution of rock mass, in which the joint and crack spacings affect the mean size and characteristic size; 3) the parameters playing a leading role in blasting fragment-size are minimum burden and hole spacing.

Finally, the researching method and results mentioned above were synthetically applied to the blasting practice in production of Huaziyu magnesium mine. The joint spacings of ore mass and rock mass, the blasting parameters and the fragment-size of 10 times production blasting were investigated and measured respectively. The calculation and analyses showed that: 1) the joints and cracks of small spacing within the eastern and western stopes at Huaziyu mine are superior in number and their fractal dimensions are 0.709 6 ~ 1.177 4; 2) the composition of natural fragment-size has the following law, i.e. below F_{50} and over F_{80}, it follows R-R distribution, but between F_{50} and F_{80}, it follows G-G-S distribution; 3) the primary factors affecting blasting fragment-size are joint frequency, hole spacing, charge density and as well as burden in proper order. In blasting, the main reasons of causing blasting fragment-size large and the higher ration of big fragment content are that the used hole spacing and burden are too small and that the charge density is too large; 4) the blasting effect of small hole diameter is better than that of large hole diameter in ore and rock mass with grown joints and cracks.

作者简介

张继春，男，1963年生于四川省大邑县；1984年毕业于重庆大学采矿工程专业；1984～1986年任教于西南工学院，从事边坡工程、爆破工程、岩石力学等方面的教学与科研工作；1989年获西安建筑科技大学工学硕士学位；1994年获东北大学工学博士学位；1994～1996年在四川大学土木、水利博士后流动站工作；现为西南交通大学土木工程学院教授，任中国岩石力学与工程学会岩石破碎工程专业委员会委员、岩石动力学委员会委员。自1986年以来，一直从事岩石爆破工程、岩土加固工程方面的科研与教学工作，参加完成6项国家级、省部级课题，其中“定向断裂控制爆破理论研究”课题荣获1993年度四川省科技进步二等奖，先后在中文核心期刊和国际、国内会议及其它重要学术刊物上发表论文30余篇。

目　　录

CONTENTS