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厦门大学

硕 士 学 位 论 文

动应力场-渗流场耦合作用下砂岩流变损伤特性试验研究

Test and Research on the Rheological Damage Properties of Sandstone under Dynamic stress field-Seepage field coupling

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摘要

机械振动、交通荷载、地震等产生的动应力场与降雨等因素所产生的渗流场耦合，会加快软岩的流变损伤，导致滑坡、崩塌、泥石流等严重的地质灾害。因此，加强对动应力场-渗流场耦合作用下软弱岩体的动态流变损伤特性的研究具有重要的理论和实际意义。论文以软弱砂岩为研究对象，利用重庆大学煤炭灾害与控制国家重点实验室的 RLW-2000M 煤岩三轴流变试验机研究了砂岩在动应力场-渗流场耦合作用下的动态流变损伤特性。具体的研究内容如下：

(1) 通过采集-钻芯-切割-打磨-浸泡等过程制备饱和的砂岩试样，根据砂岩试样的全应力-应变曲线及试验设备的实际情况合理的确定试验方案。

(2) 制备 4 组饱和的砂岩试样，试验过程中的围压和渗流压力不变，使试样分别在呈正弦变化的四种不同频率的动态荷载下振动，每一组试验的动载分四个级别施加，直至试样发生破坏，研究动载大小及动载频率对砂岩轴向变形、径向变形、轴向应变速率、径向应变速率、轴向应力-应变曲线、径向应力-应变曲线的影响特性。

(3) 制备 4 组饱和的砂岩试样，试验过程中的围压和动载频率不变，使试样分别在呈正弦变化的四种不同动载范围的荷载下振动，每一组试验的渗流压力分四个级别施加，直至试样发生破坏，研究渗流压力及动载大小对砂岩轴向变形、径向变形、轴向应变速率、径向应变速率、轴向应力-应变曲线、径向应力-应变曲线的影响特性。

(4) 基于试样在试验过程中能量耗散演化规律，选取每个试样在不同分级加载阶段下初期的一个滞回环研究，计算其能量耗散的大小，分析动载大小、动载频率、渗流压力对试样的能量耗散影响特性，从而揭示能量耗散与试样损伤演化之间的相互关系。

(5) 选取轴向动应变作为损伤变量，经理论推导得到试样的损伤度表达式，并根据试验数据得到试样损伤度的变化规律，基于能量耗散规律建立了试样的损伤演化模型，在此基础上利用 origin8.0 软件对已建立的损伤演化模型中的参数进行拟合，得到了试样的损伤演化方程。

(6) 根据已有的流变模型，建立砂岩试样的流变损伤力学模型，考虑动载和渗流对试样的耦合作用，并引入损伤演化和渗流劣化，推导了动应力场-渗流场耦合作用下的动态流变损伤方程。

关键词：动应力场-渗流场耦合，损伤变量，流变损伤特性，损伤演化方程，流变损伤模型与方程

ABSTRACT

If the dynamic stress field, which is caused by machine vibrating, vehicle loading, earthquake, and so on, is coupled with seepage field, the rheological damage of soft rock will be accelerated. As a result, serious geological disasters, such as landslide, collapse and debris flow, will be happened. So, it has important theoretical and practical significance for us to strengthen the research of dynamic rheological damage properties of soft rock under dynamic stress field-seepage field coupling. In this paper, the soft sandstone is taken as example, and the RLW-2000M coal and rock computer controlled triaxial rheological testing machine in state key laboratory of coal mine disaster dynamics and control is used as the main equipment, the dynamic rheological damage properties of sandstone under dynamic stress field-seepage field coupling is studied. The main research contents are as follows:

(1) The saturated sandstone samples are made through five steps, including collection, core-drilling, cutting, polishing, soaking. Then the test schemes are determined reasonably according to complete stress-strain curve of sandstone sample and actual situation of test equipment.

(2) Four groups of saturated sandstone samples are prepared. The confining pressure and seepage pressure are constant in the process of test, and the samples are vibrated under the sinusoidal variation loading of four different frequency. In each group of tests, the dynamic loading is applied into four grades until the sample be destroyed. The influencing properties of magnitude and frequency of dynamic loading for the axial deformation, radial deformation, axial strain rate, radial strain rate, axial stress-strain curve and radial stress-strain curve are studied.

(3) Four groups of saturated sandstone samples are prepared. The confining pressure and the frequency of dynamic loading are constant in the process of test, and the samples are vibrated under the sinusoidal variation loading of four different range of dynamic loading. In each group of tests, the seepage pressure is applied into four grades until the sample be destroyed. The influencing properties of seepage pressure and magnitude of dynamic loading for the axial deformation, radial

deformation, axial strain rate, radial strain rate, axial stress-strain curve and radial stress-strain curve are studied.

(4) Based on the energy dissipation law of the samples in the process of test, one hysteresis loop at the beginning of different classification stage is selected and the magnitude of energy dissipation is calculated. Then, the influencing properties of the magnitude of dynamic loading, frequency of dynamic loading and seepage pressure for the energy dissipation of the samples are analyzed so as to reveal the relationship between energy dissipation and sample damage.

(5) The axial dynamic strain is selected as damage variable, and the expression of damage degree is obtained through theoretical derivation, as well as the variation law of damage degree of each sample can be received. The damage evolution model of the samples is established based on the law of energy dissipation. Then, the parameters in the damage evolution model can be fitted by using origin8.0 software and the damage evolution equation of the samples is obtained.

(6) The rheological damage model of sandstone samples can be established according to the existing rheological model, and the rheological damage equation of sandstone samples which considering the dynamic loading, the degradation effect of seepage and the damage evolution, can be derived under the dynamic stress field-seepage field coupling.

Keywords: dynamic stress field-seepage field coupling, damage variable, properties of rheological damage, damage evolution equation, rheological damage model and rheological damage equation

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第一章　绪论

1.1　选题背景及研究意义

我国幅员辽阔，江河山川纵横遍布，地质环境复杂多变，地壳构造运动及内外力地质作用强烈，山崩、地震、泥石流等地质灾害现象多发。加之改革开放以来我国经济技术飞速发展，基础设施及大型工程建设的规模达到了前所未有的高度。随着西部大开发、中原举起、东北振兴、东南沿海优先发展等战略的不断推进，一大批优秀的国家重点工程项目也相继被兴建，如三峡工程、南水北调工程、西气东输工程、西电东送工程、锦屏一级、二级水电站工程、地铁隧道工程等。这些工程规模巨大，地质环境复杂，且大多数建设在软弱的岩土地基上，这些岩土地基在经历了多少年的地壳构造运动、外界荷载作用、雨水渗透作用、温度及化学腐蚀作用后，其外部形态及内部结构已经发生了很大的变化，在受到外界的扰动后其流变特性和损伤特性表现显著，产生显著的流变损伤变形进而导致大规模的突发的工程地质灾害事故。

根据中国国土资源地质公报及地质灾害公报数据，我国每年所发生地质灾害不计其数，这不仅造成了严重的人员伤亡，也带来了巨大的经济损失。2011 至 2015 年度我国由于地质问题所引发的灾害情况统计如下表 1-1 所示[1][2]。

表 1-1 2011-2015 年度我国地质灾害发生及损失统计表

年度	数目/起	地质灾害类型			死亡/人	失踪/人	受伤/人	经济损失/亿元
		滑坡	崩塌	泥石流				
2011	15664	11490	2319	1380	245	32	183	40.1
2012	14322	10888	2088	922	292	83	259	52.8
2013	15403	9849	3313	1541	481	188	264	101.5
2014	10907	8128	1872	543	349	51	218	54.1
2015	8224	5616	1801	486	299	58	138	24.9

福建省地处东南沿海，濒临西太平洋，东临台湾海峡，独特的地理位置也导致福建区域台风暴雨多发，降水强度大且集中。福建省内多高山和山丘，其

面积约占福建省总面积的 80%以上。受雨水和气候的影响，山地丘陵被风化侵蚀的较为严重，导致地表的浅表层也被大量的软弱岩体所覆盖，外加福建地区山多地少，多数的工程依山就势、削坡建设，导致形成了数量相当多的高陡边坡。特殊的地理位置和气候条件，使得福建省一直都是受地质灾害影响严重的省份之一，相关统计数据表明，福建省大概有 10000 多处可能引发地质问题的隐患点，类型多以滑坡为主，这些隐患给 20 多万人的生命和财产安全带来了极大的风险。自 20 世纪 80 年代以来，福建省重大地质灾害事故多发，造成 10 人以上死亡的多达 15 起之多，这 15 起地质灾害共造成 289 人死亡或失踪。目前，福建正实施海西经济区发展战略，填海造陆、厦门海底隧道、厦门地铁、水利水电、核能开发等大型的岩土工程建设方兴未艾，这些大型的工程建设也更易诱发软弱岩体的滑动、失稳和破坏，进而导致建筑物基础沉降、倾斜、倒塌等岩土工程事故和地质灾害[3]。

软岩的流变特性显著，软岩在恒载的作用下，其流变特性表现较为缓慢，短期内不会产生较大的变形而导致破坏。但是自然界中稳定的荷载较少，而由地震、爆炸、振动、风浪等所引起的动态荷载居多，所以探究软弱岩体在动载下的流变特性更能反映实际工程中的情况。软岩在外界动载的扰动作用下其流变特性变现的更为显著，并且较之于稳定荷载，软岩在动态荷载作用下的流变变形速率更易加快，从而引发坍塌、滑坡、地基沉降、地裂缝等重大地质灾害事故。

软岩内部的孔隙、微裂隙等缺陷也导致其具有一定的渗透特性，研究表明：软弱岩体的流变特性还与水的渗流作用关系密切。据统计：80~90%的滑坡等地质灾害事故多由水的渗流引发，90%以上的边坡破坏与水渗流产生的水压力有关，此外还有近 5 成左右的矿井和水电大坝事故是由于水的渗流作用引发的[4]。国内外有大量的地质灾害案例均是由于水的渗透作用导致原本稳定的岩土体发生失稳破坏，如国外较为出名的法国马尔巴塞拱坝在 1959 年首次蓄水时引发溃坝事故，意大利 1963 年 Vajont 拱坝在蓄水时左岸发生大型滑坡事故，美国 1976 年 Teton 坝体溃坝事故等[5][6]。国内的三峡工程在 2003 年蓄水后多处发生大面积的滑坡，导致滑坡部分或完全被水淹没等[7]，2010 年 8 月，暴雨在甘肃舟曲引发重大的山体滑坡、泥石流、崩塌等地质事故。可见，动应力场是导致软弱