

岩石灾变非连续结构与多物理场效应的透明解析与透明推演

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摘要:煤炭对于我国经济发展与能源安全起到压舱石和兜底保障的作用,在“碳达峰、碳中和”国家重大战略决策背景下,研究如何充分发挥煤炭的保障能源与战略资源的作用、实现煤炭绿色智能低碳开发利用迫在眉睫。煤炭生产开发活动打破了地层初始应力平衡,引起围岩应力场重分布,诱发工程灾害。岩石是煤炭生产开发与工程建设的主要对象,研究和解决煤炭绿色智能安全开采问题的基础理论之一是岩石力学。然而,传统的岩石力学理论在定量分析和描述煤炭生产开发活动引发的岩石灾变行为及内禀机理时存在诸多困难,人们对岩石不连续结构演化引起的应力场、变形场和渗流场的变化认识不足,缺乏定量解析内部应力、变形与渗流等多物理场的方法、理论和模型,难以对不同开采模式可能引发的工程灾害进行超前研判、预警和科学防控。解决这些基础科学与技术难题,迫切需要建立和发展颠覆性理论与变革性技术,这已成为创新发展煤炭资源绿色智能安全开发理论与技术的基础性前沿课题。围绕岩石灾变的非连续结构与多物理场效应的透明解析与透明推演,概述了岩石的三维数字重构、3D打印模型材料、透明物理模型、尺度效应、应力场、变形场和渗流场演化以及灾变机理的透明定量解析等方面的最新成果,分析了未来发展目标与面临的挑战,以求为发展非连续岩石力学与灾变分析理论,实现煤炭绿色智能开采及灾害超前预警防控提供研究基础与参考。

关键词:岩石力学;非连续结构;多物理场;透明解析;数字重构;透明物理模型;3D打印

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Transparentized solutions and interpretation for the effects of discontinuous structures and multiphysics on rock failure

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Abstract: Coal plays the cornerstone role of sustaining China's economic growth and safe energy supply. In the context of achieving peak carbon emissions before 2030 and carbon neutrality before 2060, it is urgent to

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study how to efficiently ensure the role of coal resources and achieve the green, safe, intelligent, and low-carbon development and utilization of coal resources. Underground coal production and exploitation breaks the initial stress balance of rock formations and causes the stress redistribution in the surrounding strata, inducing rock failure and engineering disasters. Rock mechanics, as a branch of continuum mechanics, has been one of the fundamental theories used to solve the problems related to green, intelligent, and safe coal mining. However, the traditional rock mechanics theory has significant difficulty in quantitatively analyzing and describing the failure physics and mechanisms of rocks which inherently involve multiscale discontinuities. Insufficient knowledge and lack of accurate descriptions and reliable models of the internal stress, strain and seepage fields in discontinuous rocks have impeded the pre-judgment, early warning, and effective control of coal mining-induced disasters. Thus, it is critical to develop novel theories and innovative technologies for achieving the green, intelligent, and safe coal mining and utilization. This paper presents the state-of-the-art research of the transparentized solutions and interpretation for the effects of internal discontinuities and multi-physical fields on mining-induced rock failure. The authors briefly reviewed and discussed the recent progresses, prospects, and challenges in three-dimensional (3D) digital reconstruction models, 3D printing and materials, printed transparent models, size effects, the evolution of stress fields, deformation fields, and seepage fields, as well as the transparentized solutions for rock failure physics. The aim is to provide a research bases and reference for the development of discontinuous rock mechanics and failure analysis theories, as well as the realization of green, safe, and intelligent coal mining, the early warning and prevention of mining-induced disasters.

Key words: rock mechanics; discontinuous structures; multi-physical fields; transparentized solutions; digital reconstruction; transparent physical models; 3D printing

煤炭对我国经济社会发展与能源安全作出了巨大贡献,在我国能源体系中起着压舱石和兜底保障作用。我国能源资源禀赋特征是“富煤、贫油、少气”,已探明化石能源储量中煤炭占比达 94%^[1]。习近平总书记在近期的中央经济工作会议上指出“要立足以煤为主的基本国情,抓好煤炭清洁高效利用,增加新能源消纳能力,推动煤炭和新能源优化组合。要狠抓绿色低碳技术攻关”^[2]。2020 年,习近平总书记在第 75 届联大一般性辩论上提出“二氧化碳排放力争于 2030 年前达到峰值,努力争取 2060 年前实现碳中和”^[3]。在“碳达峰、碳中和”国家重大战略决策背景下,深入研究如何充分发挥煤炭的保障能源与战略资源的作用、实现煤炭绿色低碳开发与洁净利用迫在眉睫。

地球深处蕴藏着丰富的煤炭资源,岩石是煤炭资源开发与工程建设的主要对象,狭义上,岩石指实验室尺度的岩块,广义上,岩石指工程尺度的岩体。煤炭开发与工程建设活动打破了初始地应力场的平衡状态,引起岩石应力场重分布,诱发冲击地压、瓦斯突出、矿震、生态环境破坏等重大灾害^[4-7]。然而,人们对煤炭赋存状态、岩石构造演化以及生产开发活动的影响认知还不够,传统开采理论与技术难以精准探测和描述岩石复杂结构及开采引发的演化过程,也缺乏对开采岩石力学行为与致灾机理的科学解析和准确表征,因而难以对煤炭生产与工程建设活动可能引发

的工程灾害进行超前预警和科学防控。解决这些基础科学与技术难题已成为创新发展煤炭资源绿色智能安全开发理论与技术的重大基础性前沿课题。

煤炭绿色智能安全开采基础理论之一是岩石力学。然而,传统的岩石力学理论在定量分析和描述生产开发活动引发的岩石结构与力学行为变化及灾变机理时存在诸多困难,例如,①天然岩石赋含大量跨尺度、几何非规则的孔隙、裂隙、节理或层理等非连续结构^[8-10],传统的岩石力学方法,在连续均匀介质假定的基础上,在代表性体元(Representation Volume Element, RVE)尺度上,研究岩石的应力、应变、渗流与灾变等行为,建立岩石的宏观本构模型、强度准则和失效判据等,难以准确描述和定量解析岩石内部非连续结构特征及其对岩石力学行为与孕灾-致灾机理的影响^[11-12]。同时,由于人们对 RVE 尺度内不连续结构引发的应力场、变形场和渗流场的变化认识不足,导致确定合理的 RVE 尺度非常困难,基于连续均匀假设所建立的本构模型、强度准则和失效判据可能失去代表性,造成采用传统的理论模型与数值方法解决工程实际问题时存在较大偏差^[10]。这些困难制约了构建考虑内部非连续结构效应的岩石力学与灾变分析体系;②开采扰动引发的岩石内部非连续结构演化、物质-力学相互作用与多物理场耦合致灾是一个“看不见、摸不着”的“黑箱”过程,现有的岩石力学理论和方法难以直观显示和准确描述^[13-14],缺乏定

量解析这种“黑箱”内部应力场、变形场和渗流场等多物理场的方法、理论和模型;③由于难以准确获取、直观显示和定量解析生产与建设活动引发的岩石非连续结构演化、多物理场耦合致灾机理及灾变力学特征,现有的矿山灾害防控多采用“随采随治”策略,难以超前研判不同开采方式和工艺可能引发的工程灾害的时间、位置和量级,难以实现开采灾害的超前预警和科学防控^[5,13]。岩石力学的这些基础难题已成为制约煤炭绿色智能安全开采理论与灾害防控技术发展的瓶颈,迫切需要建立和发展颠覆性理论与变革性技术。

当前新兴技术的发展为直观描述和定量表征岩石内部复杂非连续结构、应力场、变形场、渗流场与灾变机理创造了条件。针对岩石内部非连续结构、物理场演化及灾变行为难以透明显示和定量解析的难题,笔者采用高分辨 μ CT成像、3D数字重构、3D打印、光弹性法、数字图像相关法和三维流场示踪等技术和方法,提出了岩石内部非连续结构、应力场、应变场、渗流场演化与多场耦合致灾机理的透明解析与透明推演方法,基本思路是:构建含复杂非连续结构RVE尺度的岩石数字模型和透明物理模型,研制具有与天然岩石相同或相近物理力学性能、具有应力敏感性的透明3D打印材料,研究确定合理尺寸的非连续岩石RVE单元;采用透明可视化方法,在RVE尺度上,透明显示和定量表征岩石非连续结构特征及其对岩石内部应力场、应变场、渗流场的影响与耦合致灾机理;基于岩石多物理场的透明定量解析,建立关联内部非连续结构及物理力学效应的岩石本构模型、强度准则及灾变判据;构建RVE尺度的岩石透明模型与天然岩石非线性物理量之间的转换关系及相似律模型,形成基于RVE尺度多物理场透明解析的非连续岩石力学与灾变分析理论的基础框架。在此基础上,将实验室透明物理模型研究与工程现场探测相结合,透明显示并定量分析工程尺度下岩石结构演化、能源物质运移、力学耦合作用与致灾过程。

近年来,国内外学者围绕岩石复杂结构的三维数字重构方法、3D打印材料研制、透明物理模型制备、尺度效应、三维模型应力场、变形场和渗流场演化以及灾变机理的透明定量表征开展了大量研究。笔者简要总结了国内外学者及笔者在上述方面的研究进展,分析了未来发展与面临的挑战。本文意在为发展非连续岩石力学与灾变分析理论、实现煤炭绿色智能安全开采及灾害超前预警防控提供理论研究与技术应用参考。

1 岩石非连续结构的数字模型

1.1 非连续结构探测方法

岩石物理力学性质与灾变行为很大程度上取决于其内部非连续结构。近年来,工业X射线CT扫描(X-ray CT)、磁共振成像(MRI)和聚焦离子束电镜扫描(FIB-SEM)等先进成像技术的发展,为识别和准确表征岩石内部跨尺度非连续结构提供了有力手段。笔者基于X射线CT扫描数据构建了岩石非连续结构的三维数字模型及其RVE单元模型^[14-16]。该方法可直观显示和定量刻画岩石内部微细观尺度的非连续结构,已广泛应用于岩石力学研究^[14-18]。与CT成像技术相比,FIB-SEM是一种破坏性方法,但具有更高的分辨率,可达1~10 nm,为研究岩石内部纳米尺度非连续结构提供了有效方法,但观测区域小和破坏性限制了该技术在某些情况下的应用。MRI在空间和时间分辨率方面相对灵活,具有快速识别内部结构变化的优势,但分辨率相对较低^[19-20]。将上述方法相结合可实现岩石内部跨尺度非连续结构的直观定量观测,有利于在RVE尺度范围内定量刻画岩石复杂的内部结构并构建反映内部跨尺度结构的岩石RVE模型^[21]。

1.2 非连续结构的重构方法与模型

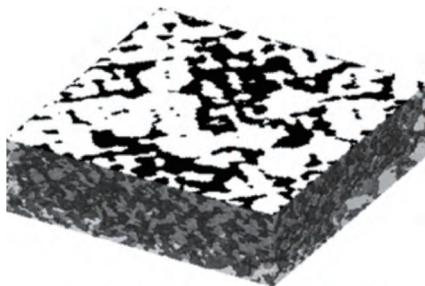
实验室及现场原位探测提供了岩石内部非连续结构的详细信息,但考虑到地层岩心钻探的难度、高精度成像的高成本以及岩石非均质非连续性带来的物理力学量对比分析的困难,发展一种便捷、经济和可重复的岩石非连续结构的直观定量描述手段十分重要。近些年,利用有限地质探测数据和计算机重构算法来重构岩石三维非连续结构的研究取得了飞速发展。随机生成、多点统计信息、模拟退火、基于过程的方法和机器学习等方法被广泛用于重构和刻画岩石内部复杂非连续结构。

随机生成方法可以简单、直接地构建出岩石内部非连续结构。例如,基于统计信息,WANG和PAN^[22]提出了一种多参数随机生成-生长的方法来生成不同类型的多孔结构;笔者改进了随机球及裂隙填充法,通过控制球及裂隙的大小和孔隙度参数来生成页岩孔隙结构^[23];为了研究粗糙裂缝的流体输送特性,笔者应用分形理论直接生成了粗糙裂缝^[23-25]。这些随机生成方法通常具有较高的重构效率,准确性取决于重构过程中所使用的关键信息。

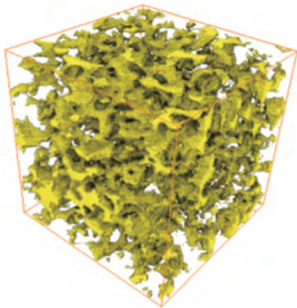
多点统计信息法^[26]使用模板扫描训练图像来提取局部多点特征,并将这些特征模式运用到新的重构图像中。重构过程中考虑了多点统计信息,可以较好

地再现多孔介质的几何形状和连通性。

模拟退火法是一种被广泛使用的重构方法^[27-32],它通过不断调换代表孔隙相与固体相的数据点对的位置来重构模型,这种方法可以将任意类型的目标函数纳入重构。但由于需要进行大量的位置调换,并生成大量的中间结构,重构速度较慢。近年来,为了提高岩石数字模型的重构精度和重构效率,各国学者在模拟退火算法的基础上,采用高阶相关函数^[27-28]、方向相关函数^[29]、优化的模拟退火算法^[24]、不同权值相关函数^[30]、多尺度重构^[31]和并行计算等方法^[32]来构建岩石非连续结构三维 RVE 数字模型。笔者基于该原理,提出了改进的并行模拟退火算法,对岩石孔隙结构进行了高效准确的三维重构(图 1)^[32]。



(a) 基于模拟退火算法的三维重构模型



(b) 基于深度学习算法的三维重构模型

图 1 岩石孔隙结构三维重构模型

Fig.1 3D reconstruction model of rock pores

基于沉积岩成岩过程来重建沉积岩孔隙结构的方法由 ØREN 和 BAKKE 率先提出^[33],该方法考虑了压实、颗粒沉积和成岩过程,具有广泛应用前景。

机器学习方法通过大量真实的岩石扫描图像来建立和训练神经网络,利用训练好的网络来生成岩石三维复杂结构^[34]。这种方法需要大量的数据样本,但神经网络训练完成后可以在较短的时间内生成具有较好相似度的真实结构(图 1(b))。受限于神经网络的能力,目前大多数重建工作主要局限于 64^3 和 128^3 的 RVE 尺度规模。特别是,由于神经网络原理的难解释性和泛化能力差等问题,该方法在重建结果的准确性和普适性等方面面临诸多挑战,有待进一步改进。

需要指出的是,尽管研究表明数字化方法可以经济有效地获取和透明显示岩石内部非连续结构,但目前研究主要集中在利用有限微观结构信息进行岩石 RVE 模型重构。使用低阶统计信息提高了 RVE 模型重构效率,但牺牲了模型精度。随着计算机运算能力进一步提高,有望采用更多的高阶统计信息来提高 RVE 模型的重构精度,这将是岩石内部非连续结构三维数字化重构与透明表征研究的发展方向。

2 3D 打印模型材料研制

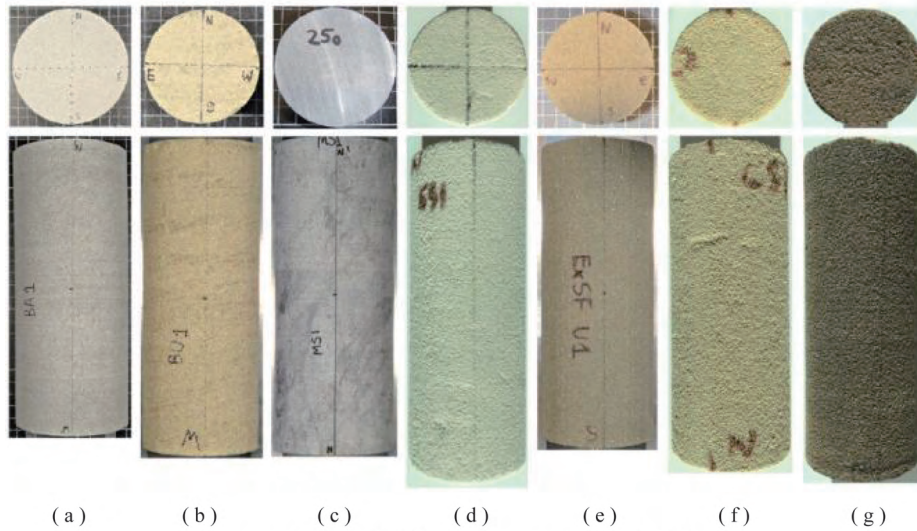
3D 打印技术已广泛应用于岩石力学研究,该技术为重复制备内部包含复杂非连续结构的岩石物理模型并定量分析非连续结构对岩石灾变力学行为的影响提供了可能性和新途径^[9]。然而,除内部非连续结构因素外,岩石物性也是影响岩石物理力学性质与灾变行为的重要因素,研制能够反映天然岩石物性的 3D 打印材料是利用 3D 打印模型开展非连续岩石灾变力学行为面临的重要挑战。

针对此问题,国内外学者采用不同 3D 打印技术,例如,光固化成型技术^[14,34]、熔积成型法^[35]、选择性烧结成型法^[35-36]等,研究了硅砂、石膏、光敏和热固性树脂等常用打印材料的物理力学性质,探究了这些材料用于制备天然岩石模型的适用性。例如, PERRAS 等^[37]对比分析了天然砂岩和 3D 打印模型的抗压强度、抗拉强度、刚度、裂纹生成、裂纹损伤阈值和应变行为等,发现 Sand-Furan 3D 打印试样的力学性能与天然砂岩最接近(图 2);ZHU 和 ZHOU^[36]研究了陶瓷、石膏、PMMA、SR20 丙烯酸共聚物和光敏树脂 5 种可打印材料在单轴压缩下的力学性能和破坏模式,指出采用立体光固化成型法(Stereo Lithography Appearance, SLA)的光敏树脂材料最适合模拟脆性和坚硬岩石,他们通过静态和动态巴西劈裂试验发现光敏树脂模型表现出与天然岩石相同的破裂行为。GELL 等^[38]研究了用于制备岩石试件的水泥、树脂和含砂混料的力学性质,指出 3D 打印试件可以实现岩样内部非连续结构的精细化复制,比传统浇注制样更具优势。

除了如何使 3D 打印模型具有与天然岩石一致的非连续结构和物性外,如何能够准确反映和量化非连续岩石内部应力场也是 3D 打印材料研究面临的重要挑战。为了获得高应力敏感性、可用于透明显示和定量表征岩石内部应力的 3D 打印材料,笔者利用美国 Stratasys 公司生产的 Object Connex 500 和 J750 3D 打印机,制备了用于打印材料物理力学性能测试的标准试件,详细研究了 3D 打印材料 VeroClear 的组

成分^[34]、基本物理力学性能^[40-41]、打印成型方式及模型后处理的影响^[40]、应力双折射效应^[40,42](图 3(a), (b))、光热曲线(图 3(c))^[42]、应力冻结性质^[42,39](图 3(d))以及高低温下的塑性及脆性性质^[40]等。其中, Object Connex 500 和 J750 打印机的最小成型厚度分别为 16 和 14 μm ^[14,39]。实验结果表

明: VeroClear 具有良好的应力双折射效应和应力冻结性能, 这种打印材料在一定条件下具有与煤、砂岩相似的物理力学性质与破坏模式, 而且可用于透明显示和定量表征受载破坏过程中岩石非连续结构内部应力场的演化, 为透明解析岩石 RVE 模型内部三维应力场提供了条件和基础。



(a)-(c) 天然砂岩样品; (d)-(g) 3D 打印砂岩样品

图 2 天然砂岩样品及 3D 打印砂岩样品^[35]

Fig.2 Natural sandstone samples and 3D printed sandstone samples^[35]

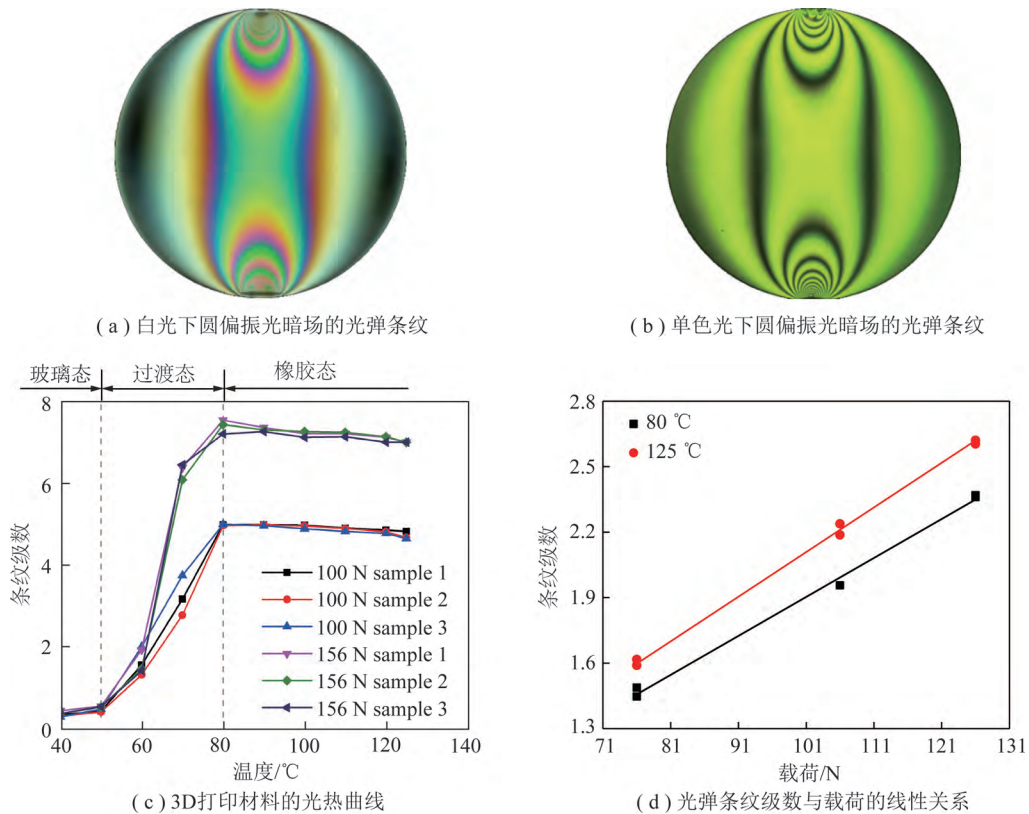


图 3 3D 打印材料的物理力学性能

Fig.3 Physical and/or mechanical properties of 3D printing materials

需要指出的是,尽管国内外学者做了大量工作,但从材料物性及物理力学性能角度来看,3D 打印模型材料与天然岩石尚有不小差距,还需进一步研究和改性现有的打印材料。根据目前的研究结果,改善 3D 打印材料性能可有以下途径:① 在分子结构层面设计打印材料;② 调整模型打印方式与参数;③ 增添不同成分的微观结构来模拟天然岩石并改进打印模型的物理力学性质;④ 优化打印模型后处理等,希望应用这些技术使打印模型能够代替或更好地模拟天然岩石。

3 岩石非连续结构的透明物理模型

利用现场和实验室探测技术及数字重构方法可以建立直观定量描述岩石 RVE 单元内跨尺度非连续结构的数字透明模型。然而,由于人们对 RVE 尺度内不连续结构引发的应力场、变形场和渗流场的变化及其内禀物理机制认识不足,在数字模型基础上,将基于连续性假设所建立的本构模型、强度准则和失效判据用于岩石灾变数值模拟分析,预测结果往往与工程实际存在较大偏差^[43-44]。因此,开展物理模型实验揭示岩石灾变“黑箱”过程与物理本质、建立准确的体现内部非连续结构效应的本构模型、强度准则与

失效判据是解决工程实际问题的必由之路。然而,如何重复制备含复杂内部结构的物理模型一直是岩石物理模型实验研究的一个难题。

近年来,快速发展的 3D 打印技术为解决上述难题提供了途径。人们基于数字模型与 3D 打印模型材料,采用不同的 3D 打印技术制备了与天然岩石物性相似且内部结构一致的物理模型。例如,为了研究打印制备的孔隙模型的力学性质和渗流特征,ISHUTOV 等^[45-47]利用 CT 成像和 3D 打印技术制备了天然砂岩孔隙结构的物理模型(图 4)。JIANG 等^[48]打印制备了与天然岩石内部节理分布一致的物理模型,指出 3D 打印技术能够制备含有复杂孔隙和裂隙结构的岩石模型,可用于岩石力学性质研究。然而,由于采用不透明 3D 打印材料,上述方法制备的岩石物理模型无法直观显示和定量表征岩石内部物理场变化与灾变过程。为了透明显示和定量解析岩石内部非连续结构及物理场演化与灾变过程,笔者采用自主研发的原位三轴加载 CT 成像系统(美国、英国与中国发明专利)^[49-51]与分形数字重构方法^[27],应用研制的透明 3D 打印材料^[14,39],制备了具有与天然岩石一致非连续裂隙、孔隙结构及相近物理力学性质的岩石透明物理模型(图 5)^[14,42]。

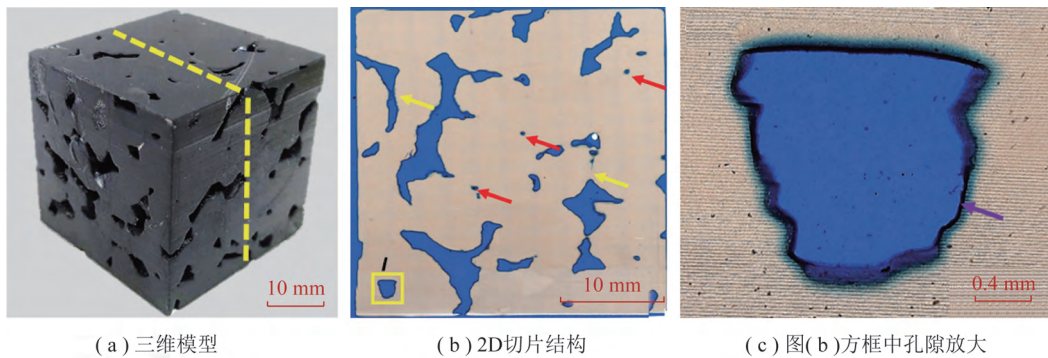


图 4 3D 打印孔隙岩石模型^[47]

Fig.4 3D-printed models of porous rocks^[47]

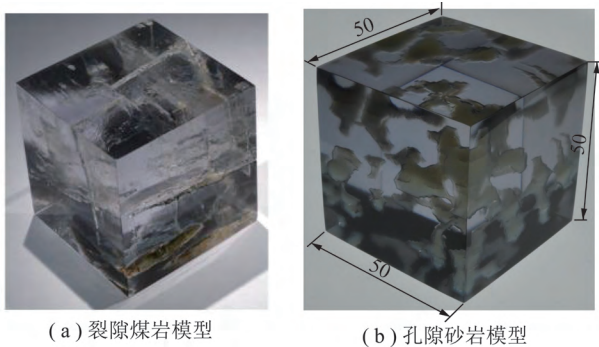


图 5 岩石透明物理模型^[14,42]

Fig.5 Transparent models of rocks^[14,42]

为了模拟赋含非均质非均布颗粒与矿物充填的岩石,作者基于多材料打印技术,采用不同力学性质的材料复制天然岩石中的不同成分^[52-53],例如,笔者采用两种不同打印材料模拟骨料和基体,并按照骨料和孔隙的实际分布打印制备了混凝土透明模型(图 6)。

值得关注的是,天然岩石含有大量跨尺度的孔隙、裂缝、颗粒和节理等微结构,在 CT 扫描识别精度范围内,部分微结构在 CT 图像中可能仅占有 1 个体像素,可采用体像素打印技术制备这类模型^[55-56]。体像素打印是一种在体像素尺度上使用多种材料进行 3D 打印的技术,可以对每个体像素赋予不同的材

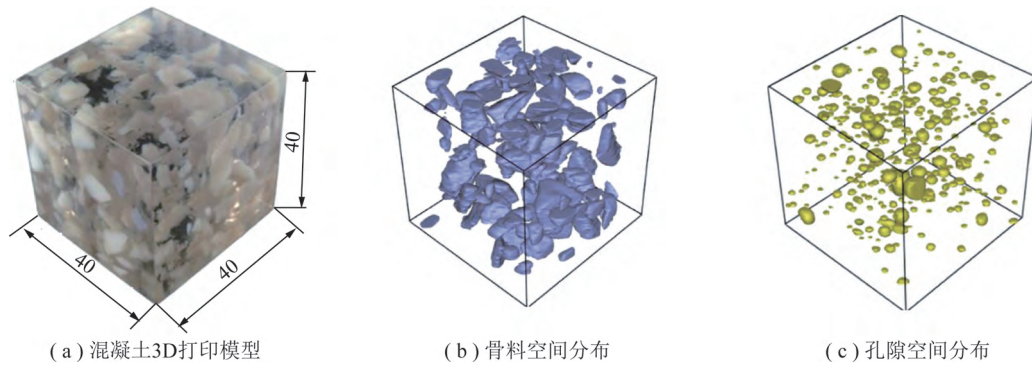
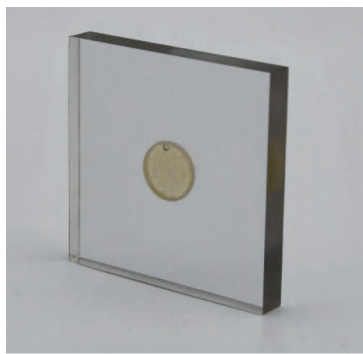


图 6 混凝土透明模型^[52-53]

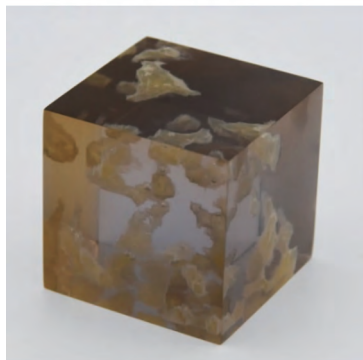
Fig.6 Transparent model of concrete ^[52-53]

料属性。对于内部组成极其复杂、跨尺度且难以精确构建数字模型的非连续结构,可以直接在 CT 图像的基础上,采用体像素打印方式制备透明物理模型,该方法将大幅度提高复杂物理模型的制备精度。

此外,为了模拟天然岩石孔隙或裂隙中的流体介质(油、水、气等),笔者采用固液两相打印技术,实现了包含流体介质的三维 RVE 模型一体化打印制备。图 7 为打印制备的内嵌流体的方板圆孔模型和孔隙结构模型,液体顶部留有微小气泡。结合体像素 3D 打印技术,通过设计固液材料的体像素空间分布,可以实现任意位置处孔隙、裂隙包含不同液体的三维模型制备。



(a) 方板圆孔



(b) 孔隙结构

图 7 内嵌液体的方板圆孔和孔隙结构的透明 3D 打印模型

Fig.7 3D-printed models of a square plate embedded a circle pore and a porous rock, filled with liquids

4 RVE 模型尺度

三维数字重构和 3D 打印技术为实现岩石 RVE 模型内部非连续结构的透明解析、发展考虑内部非连续结构特征的岩石力学理论提供了条件和基础。利用 RVE 尺度模型研究岩石的应力、应变、渗流与灾变等行为,建立反映内部非连续结构特征的岩石本构模型、强度准则和灾变判据,首先需要厘清岩石内部非连续结构特征及其对岩石力学行为与灾变行为的影响,并确定有代表性的 RVE 模型尺度。BELL 和 SIEGMUND^[57]开展了不同厚度 3D 打印模型的三点弯曲断裂实验,分析了 1~5 mm 内模型强度和断裂韧性的尺寸效应;AKIYAMA 等^[58]通过四点弯实验研究了模型尺寸对基于 FDM 技术的打印模型力学性能的影响。笔者测试了采用不同光敏打印材料制备的不同尺寸的含复杂孔隙和裂隙结构的 3D 打印模型的抗压强度、抗拉强度、弹性模量、泊松比、屈服强度、断裂韧性等,分析了岩石打印模型的尺寸效应(图 8),图 8(a)数据是根据至少 3 个重复试件实测结果计算获得。实验结果表明:3D 打印 RVE 模型体现出与天然岩石一致的尺寸效应,这为定量分析岩石内部非连续结构效应及其对岩石灾变力学行为的影响,确定含不同类型非连续结构的 RVE 单元尺寸提供了基础和依据。

5 岩石内部应力场的透明解析

5.1 二维模型应力场透明解析

为了揭示复杂非连续结构对岩石灾变行为的影响机制,笔者采用 3D 打印技术制备了天然岩石非连续结构的二维透明模型,采用光弹性实验方法,通过改进相移和解包裹算法,定量解析了荷载作用下非连续结构全场应力分布特征与演化规律^[14,39-42,52-54,61-62,64],为认知和解析岩石灾变行为的

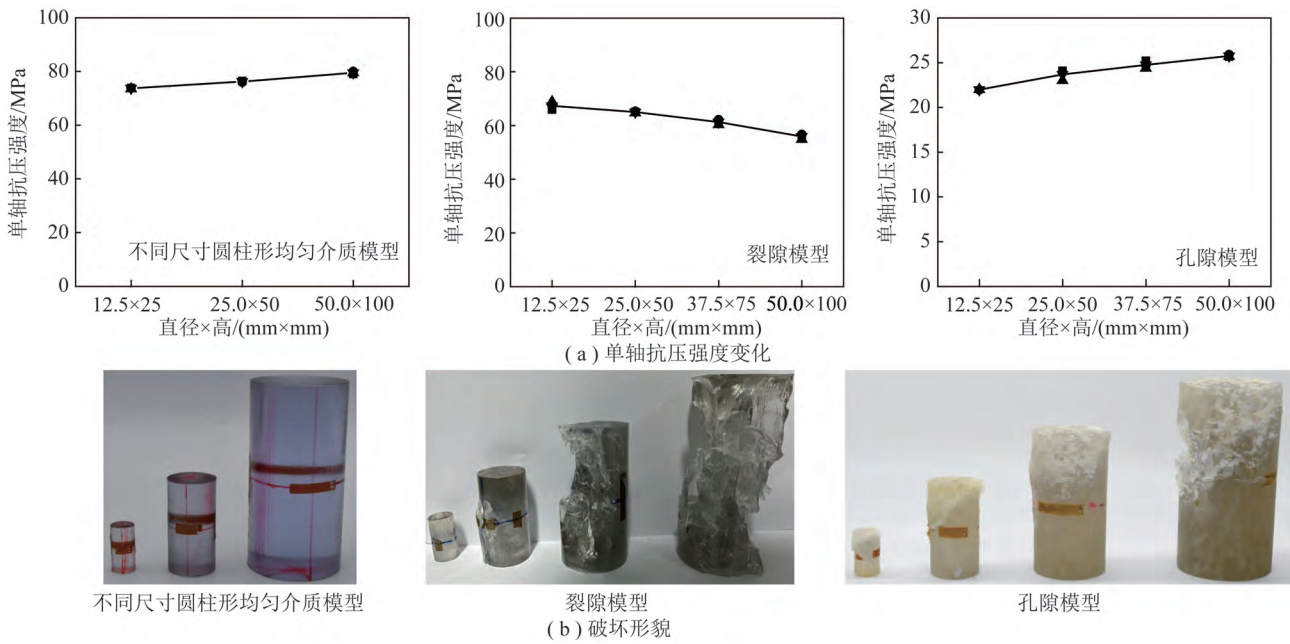


图 8 岩石 3D 打印模型尺寸效应的实验结果

Fig.8 Experimental investigation on the size effects of 3D-printed rock models

内在物理机制创造了条件。例如,笔者基于岩石裂隙结构的 CT 图像,制备了天然裂隙的二维透明 RVE 模型,发展改进了相移和解包裹算法,获得了外部荷载作用下裂隙结构全场剪应力和主应力差(图 9)^[62]。此外,笔者还模拟岩石粗糙断层结构,打印制备了粗糙断层的二维透明 RVE 模型,设计了断层剪切变形的光弹性实验,开发了非连续结构光弹性应力场的定量提取算法,定量解析了断层滑移时断层区域全场主应力差和剪应力分布与演化规律(图 10),建立了粗糙面起伏角与断层周边应力场的定量关系^[64]。采用

类似方法,作者打印制备了隧道衬砌与围岩结构的二维平面模型,提出了围岩衬砌结构全场应力的实验提取与定量解析方法,获得了外载作用下围岩衬砌结构全场主应力差与剪应力分布及演化规律(图 11)^[65],为定量表征衬砌结构及管片界面应力分布、验证数值模拟结果提供了方法和途径。类似的,MISSERONI 等^[66]通过可视化内含刚性颗粒模型周边光弹性条纹的分布,分析了刚性颗粒模型周边的应力集中和应力场分布特征;DANIELS 和 HAYMAN^[67]通过颗粒光弹模型,解析了不同节理结构特征对岩石内部应力场的

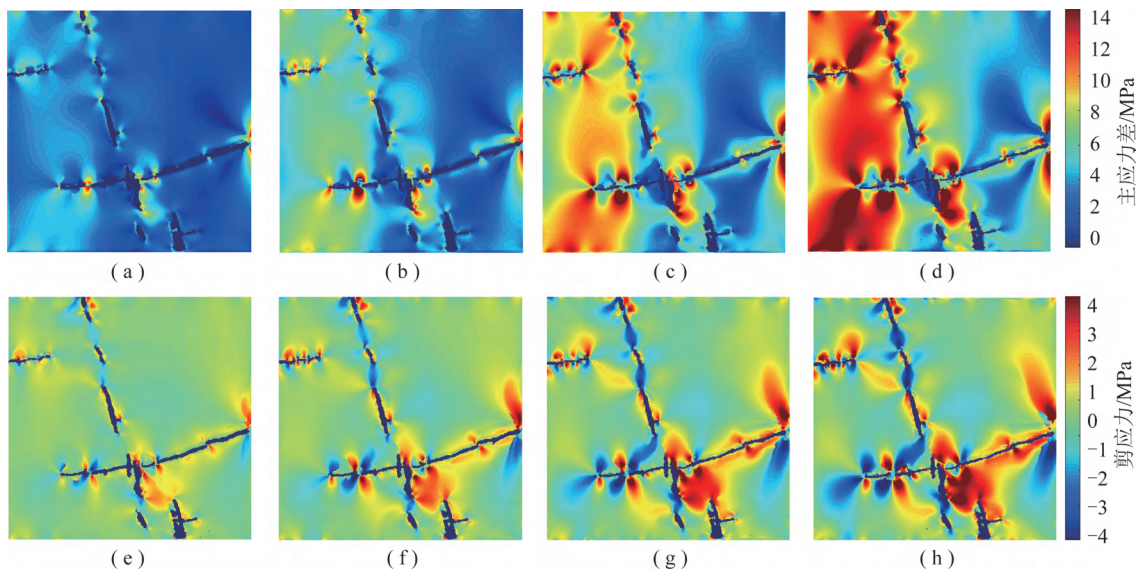


图 9 岩石裂隙结构 2D 透明模型及不同轴向载荷作用下裂隙区域应力场演化的解析结果^[62]

Fig.9 2D transparent model of rock fractures and the evolution of stress fields under different uniaxial compressive loads^[62]

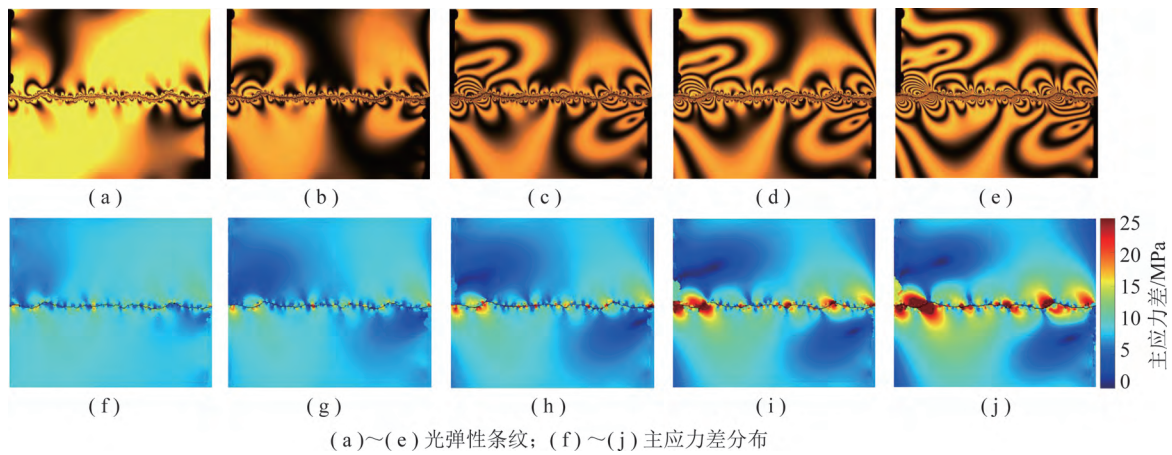


图 10 岩石粗糙断层 2D 透明模型及剪切位移变化时断层周边应力场分布演化的解析结果^[64]

Fig.10 2D transparent model of a rough fault and the distribution and evolution of stress fields under different shear deformations^[64]

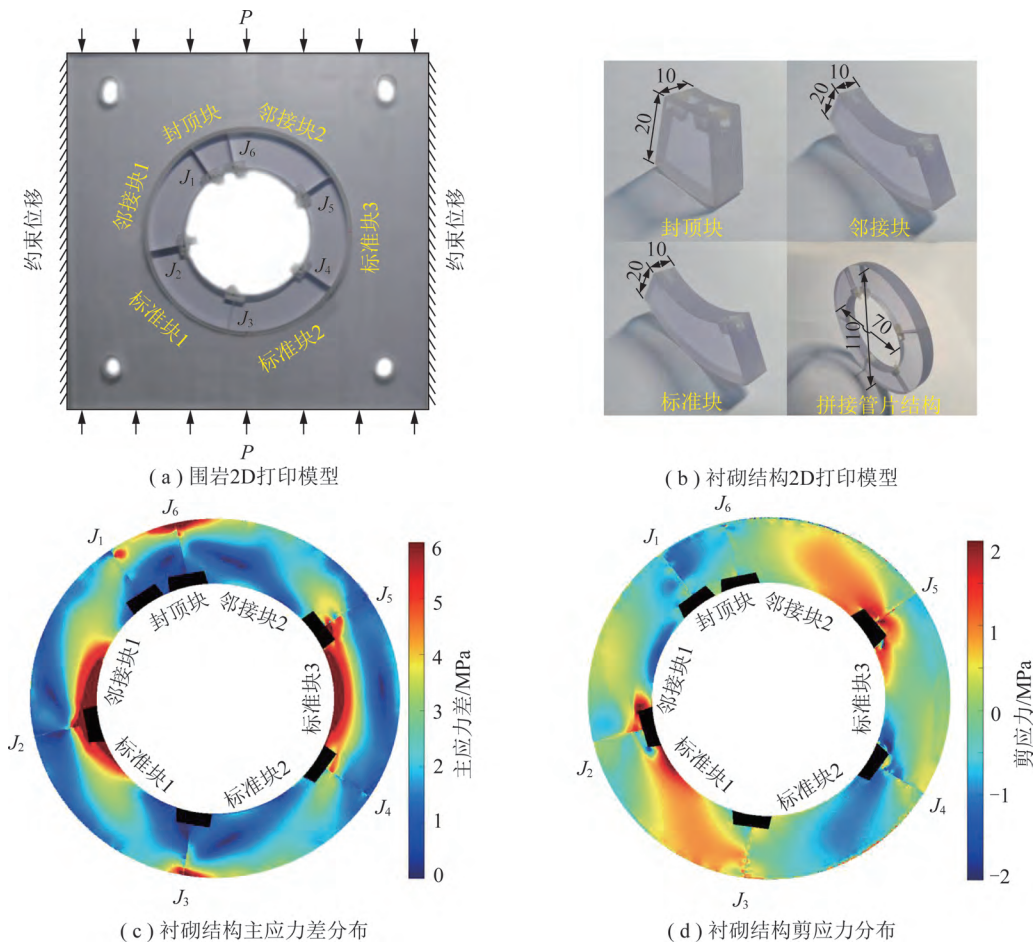


图 11 衬砌结构应力场的透明解析结果^[65]

Fig.11 Transparentized solutions to the stress fields of lining structures^[65]

影响;BIGONI 和 NOSELLI^[68-69]通过建立墙体结构的光弹模型,分析了承载梁压缩引起的墙体内部压应力分布的特征;GHISLAIN 等^[70]建立了地质断层的光弹模型,利用光弹性条纹和主应力迹线,分析了断层周围应力场(图 12);SOLIVA 等^[71]和 LUNINA 等^[72]利用地质断层的光弹性模型,定量解析了断层周边应力场的分布与演化。

5.2 三维模型应力场透明解析

岩石非连续结构二维模型应力透明解析为认知和量化非连续结构对岩石灾变行为的影响、构建非连续岩石力学理论提供了途径和支撑。然而,天然岩石包含复杂的三维结构,透明显示和定量解析外载作用下岩石内部三维应力场分布及演化对于阐释岩石结构整体灾变机理和预测工程灾害发生的位置与量级

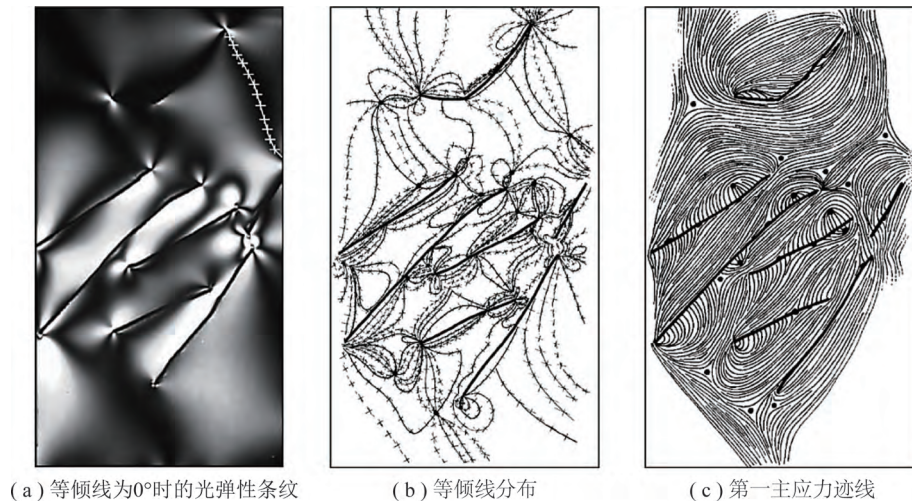


图 12 断层周边应力场定量解析结果^[70]

Fig.12 Quantitative solutions to the stress fields near faults

具有重要意义。

光弹性应力冻结是一种获取和分析三维连续均质模型内部应力场的有效方法,该方法是在温箱中对光弹性模型施加固定荷载,经历温度升降循环,光弹性材料在温升过程中分别出现液态相和弹性相,降温时液态相固化,模型内部应力被“冻结”下来。对“冻结”后模型进行不同位置的切片,通过观测切片的光弹性条纹来解析三维模型内部全场应力分布^[73-78]。然而,天然岩石结构复杂,传统的光弹性应力冻结法难以制备包含众多跨尺度孔隙、裂隙、颗粒等不规则结构的三维模型,加之缺乏有效的针对非连续结构应力场的提取算法,实现非连续岩石内部三维应力场定

量解析一直是个难题。

针对上述问题,笔者采用高精度 CT 成像、3D 数字重构和 3D 打印技术,在二维模型应力解析方法的基础上,通过研制高应力敏感 3D 打印材料、改进光弹性应力冻结法和发展针对复杂结构的应力场提取算法等措施,提出了非连续岩石内部三维应力场的透明定量解析方法^[14,41-42,52-53],为实现岩石 RVE 模型内部复杂三维应力场的透明解析、构建基于 RVE 内部非连续结构效应的岩石力学理论提供了实验基础与理论支撑。例如,图 13 展示了裂隙煤岩三维透明模型内部不同位置处的应力条纹^[14];图 14 给出了孔隙岩石三维透明模型内部不同位置处的应力条纹与

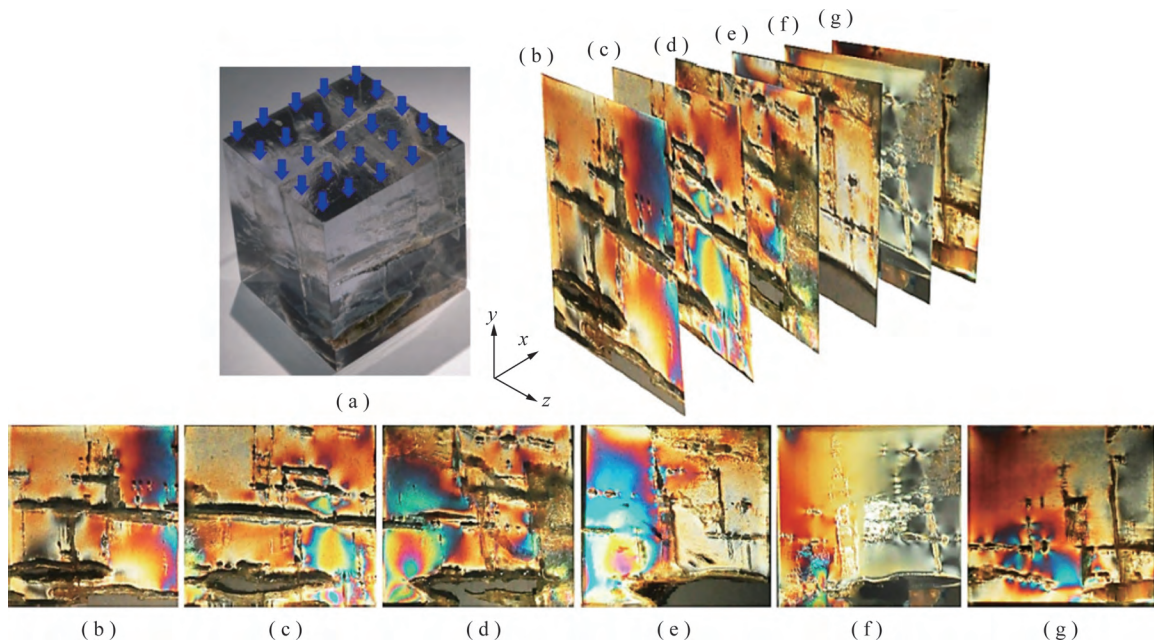


图 13 裂隙煤岩三维透明模型内部不同位置处的应力分布特征^[14]

Fig.13 Stress distribution at various positions inside a 3D transparent model of fractured coals^[14]

定量解析结果^[42];图15为非均质砂砾岩三维透明模型内部不同位置处的应力分布解析结果^[53],该结果直观显示和量化了相邻颗粒间的高应力分布特征,为阐释非均质砂砾岩变形破坏的内部非均质非均布颗粒效应及应力场演化提供了实验证据及依据;图16直观显示和定量表征了轴向压缩荷载作用下不同荷载阶段裂隙煤岩内部三维应力场的分布与演化特征。

为了揭示开采过程诱发巷道围岩灾变机理和超

前预测采动围岩破坏的位置和量级,笔者基于矿区现场三维地质勘探信息,利用3D打印技术,制备了回采巷道和回采工作面的三维缩尺透明物理模型(图17),模型中的煤层及覆岩采用与其物理力学性质相近的3D打印模型材料制备^[79]。采用上述应力解析方法,透明显示和定量表征了不同掘进位置处回采巷道围岩的应力分布大小与演化规律,为超前预警不同开采方式可能诱发的巷道与工作面围岩灾变提供了研究与定量分析手段。

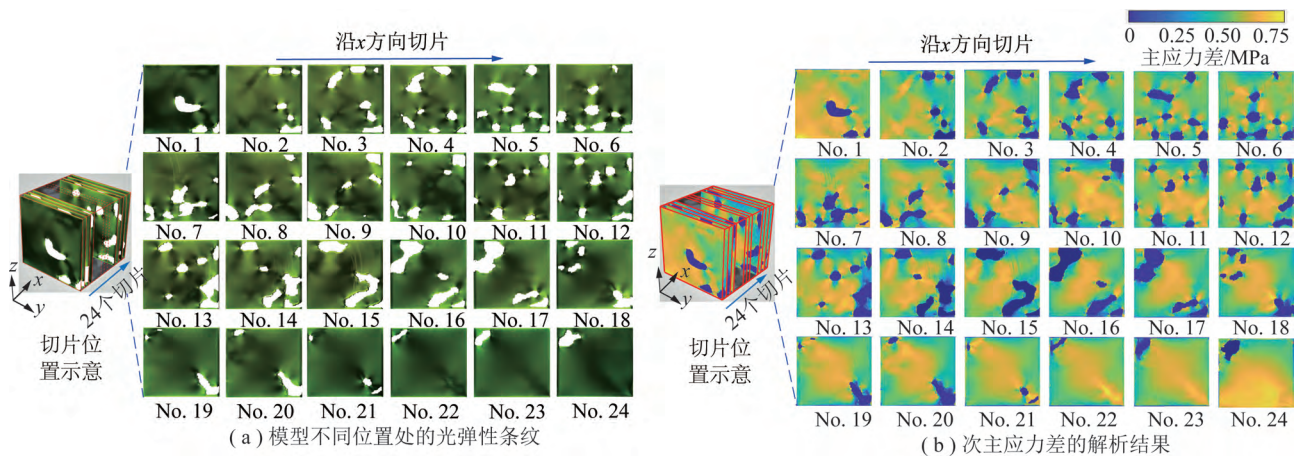


图14 孔隙岩石模型内部应力场的透明解析^[42]

Fig.14 Transparentized solutions to the stress fields inside porous rock models^[42]

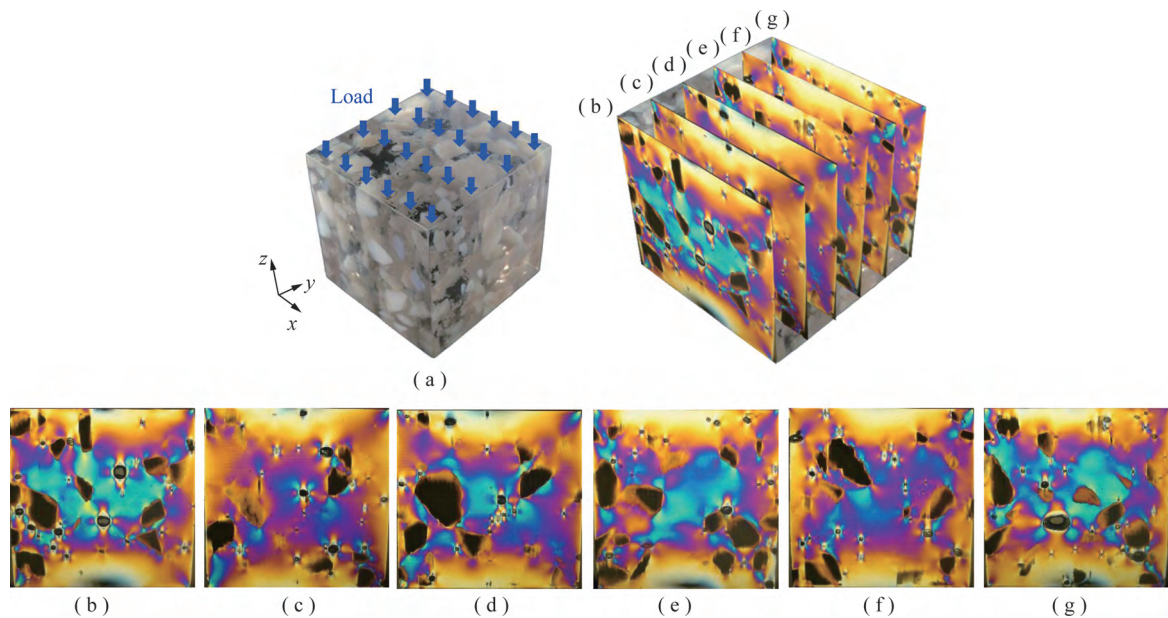


图15 非均质砂砾岩模型内部应力场的透明解析^[53]

Fig.15 Transparentized solutions to the stress fields inside heterogeneous glutenite models^[53]

5.3 动态应力场的透明解析

准确获取和量化岩石全场应力连续动态演化与非连续结构效应对应于揭示矿山岩爆、瓦斯突出、地震等动力灾害的内禀物理机理至关重要。国内外众多学者发展了动态光弹性实验方法来获取和分析岩石

应力场的动态演化特征^[80-95],例如,相移法^[86-87]、RGB法^[88-92]、载荷步法^[93]、载波法^[94]和焦散线法^[96-99]等。但由于岩石非连续结构模型制备困难以及动态应力场的连续高速变化特征,传统的岩石动态应力场表征主要集中于简单结构模型以及应力场演

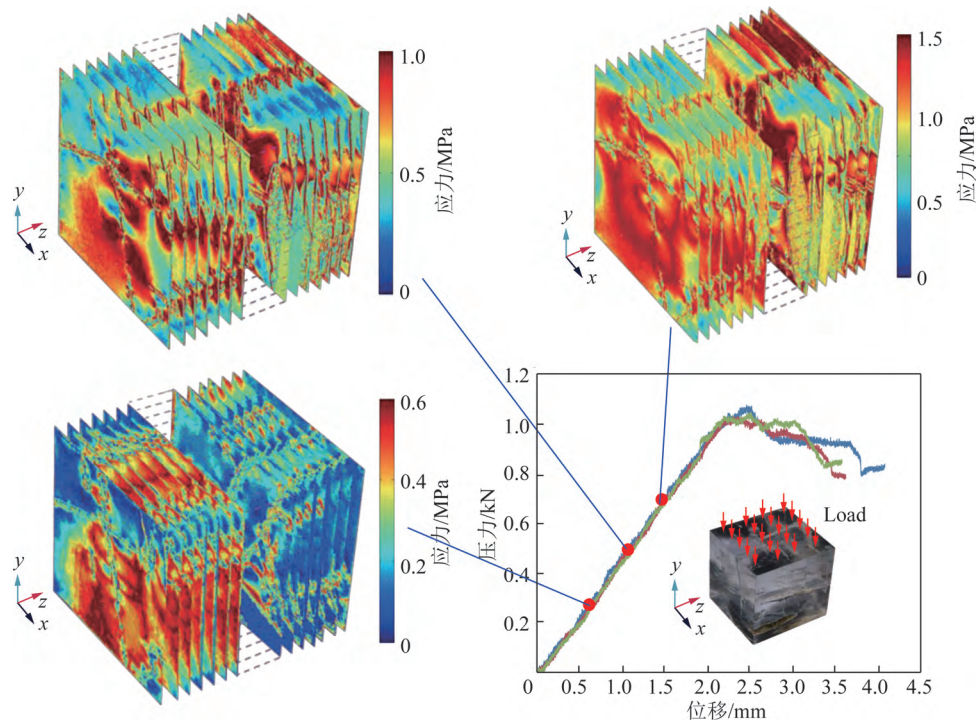


图 16 轴向压缩荷载作用下不同阶段裂隙煤岩内部应力场的分布与演化特征

Fig.16 Distribution and evolution of the stress fields inside a fractured coal under different compressive loads

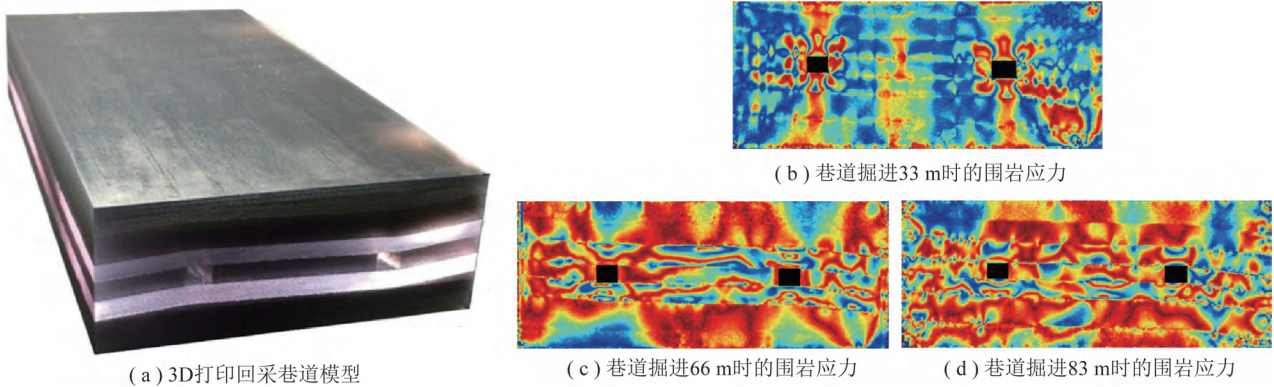


图 17 回采巷道围岩应力场的定量解析与透明推演^[79]

Fig.17 Quantitative solution and transparentized interpretation of the stress field in mining roadways^[79]

化的定性或半定量分析^[95],难以直观显示和定量解析复杂岩石结构的动态应力场演化特征。

针对上述问题,笔者利用 3D 打印技术制备了内嵌梭形裂纹的透明圆盘模型,通过对径压缩光弹性实验以及改进动态光弹条纹提取算法,获取并定量解析了裂纹尖端应力场特征及其与裂纹扩展速度之间的对应关系^[81];对于复杂非连续结构内部动态应力场定量解析难题,作者提出了一种定量解析连续载荷作用下复杂非连续结构模型内部全场应力演化的方法^[54,61,100],获得了连续加载下复杂孔隙模型内部的主应力差分布与演化规律(图 18),该方法适用于定量解析冲击或爆炸载荷作用下复杂岩石结构模型内部应力场,但前提是能够清晰地获取快速连续变化的动态光弹条纹。

由于存在大量不规则天然裂隙,岩石内部裂隙三

维扩展行为及起裂判据一直是岩石断裂与灾变理论研究的热点和难点问题。岩石三维裂纹扩展过程中的应力场特征对于理解和定量分析裂纹起裂、扩展、转向和汇聚行为、建立裂纹非稳定扩展失效判据至关重要。然而,传统实验方法在制备三维裂纹模型以及获取裂纹三维扩展过程中的应力变化等方面存在困难,三维裂纹连续扩展过程中的应力场透明显示与定量描述尚未得到解决。针对此问题,笔者采用 3D 打印技术和所研制的应力敏感 3D 打印材料,制备了含内嵌非贯穿型裂纹和贯穿型裂纹的透明模型,通过模型受压的光弹性应力冻结实验,利用改进的光弹条纹分析技术和应力场提取算法,获得并定量解析了裂纹三维扩展过程中模型应力全场特别是裂纹尖端区域主应力差和剪应力的分布及演化特征(图 19)^[101-102]。

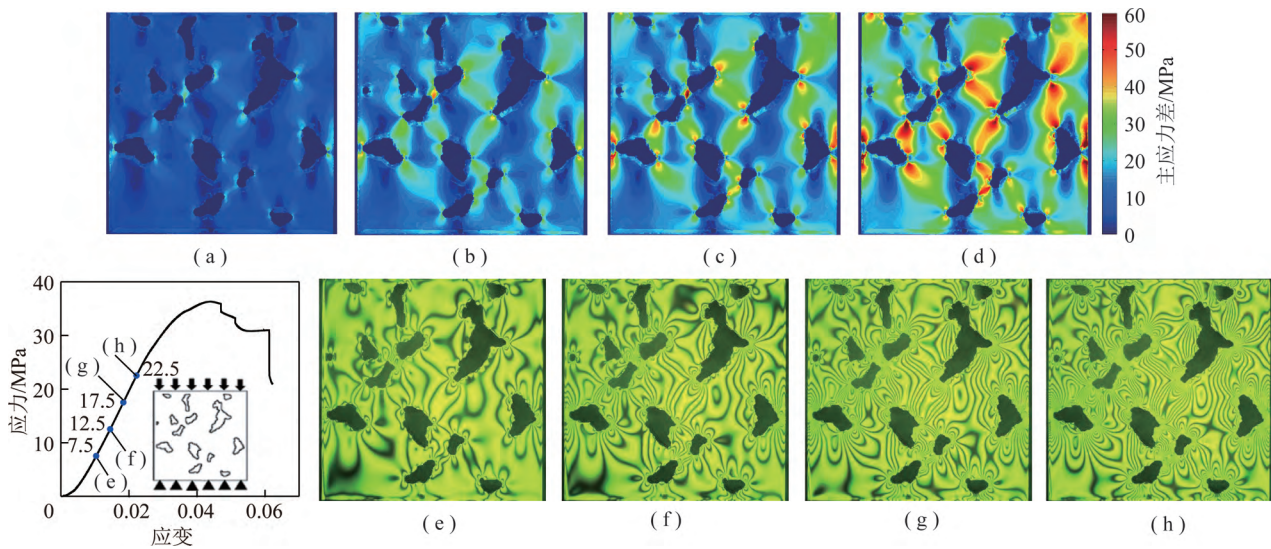


图 18 载荷连续作用下不同加载阶段复杂孔隙结构模型内部主应力差全场分布与演化规律^[54]

Fig.18 Distribution and evolution of the principal stress difference inside a porous rock model under different continuous compressive loads^[54]

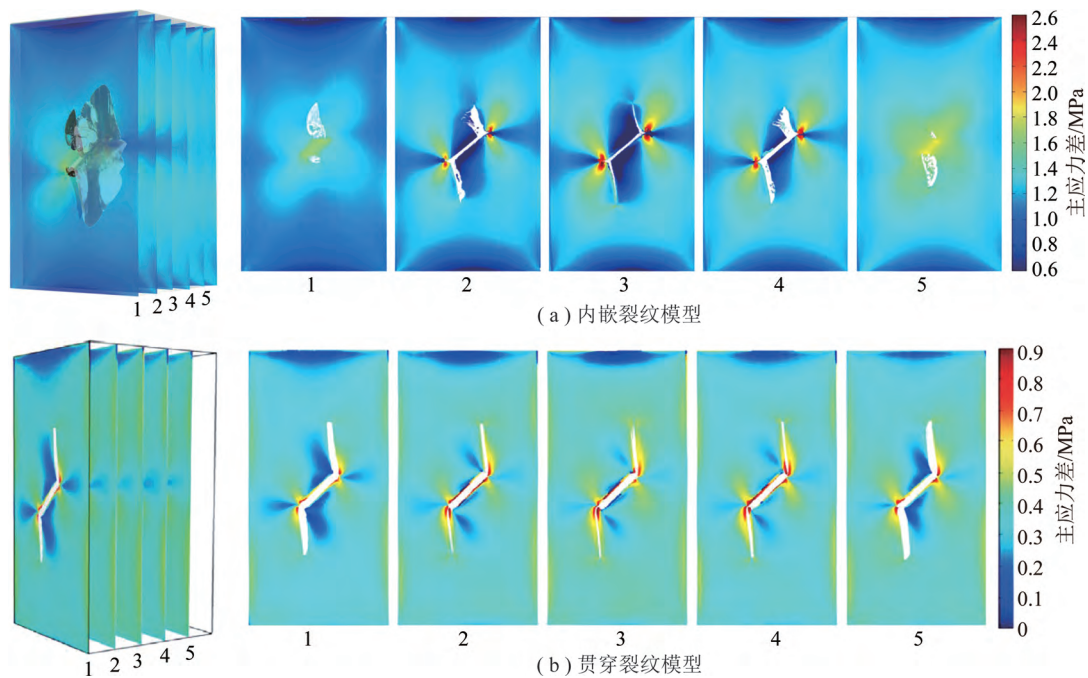


图 19 三维内嵌裂隙和贯穿裂隙扩展过程中内部不同位置处主应力差的透明解析^[101-102]

Fig.19 Transparentized solutions to the principal stress differences at different positions inside the 3D models containing embedded and penetrated fractures^[101-102]

6 岩石内部应变场的透明解析

直观显示和定量表征岩石内部变形破坏程度和集中分布区域对于理解岩石整体变形破坏机理具有重要意义。然而,目前常用的数字图像相关法(Digital Image Correlation, DIC)和表面三维 DIC 技术只能测量岩石表面和离面的变形,难以用于量测岩石内部变形,迫切需要发展内部三维变形场的直观定量

表征的方法。借助三维成像技术,如微焦点 CT、共聚焦显微镜、磁共振成像等技术,可以获得岩石样品的三维图像,基于此, BAY 等提出了数字体图像相关法(Digital Volume Correlation, DVC)来量测受压骨骼内部应变场^[103]。近年来, DVC 方法得到迅速发展和应用^[104-110]。但如何提高内部微小应变的测量与计算精度一直是 DVC 法面临的主要挑战。根据配准算法的不同,将 DVC 方法分为基于子集的局部

DVC (Local DVC, L-DVC) 和基于有限元的全局 DVC (Global DVC, G-DVC) 两种主要方法。相比之下, L-DVC 计算效率高, 在计算参数相同的情况下, G-DVC 的精度略高于 L-DVC, 尤其是当子集尺寸较小时^[111-113]。针对岩石内部非连续结构特征, 笔者提出了多尺度子块体搜索和亚体素平移方法 MS-DVSP (Multi-scale and Shifting Digital Volumetric Speckle Photography), 显著提高了复杂结构内部三维变形的测量精度^[114-115], 透明显示和定量解析了荷载作用下煤岩^[116] (图 20)、红砂岩^[117] 和混凝土^[118] 等内部三维变形的分布与演化规律, 为构建基于内部应力场和应变场透明解析的非连续岩石本构关系与灾变准则提供了途径和基础。

值得关注的是, DVC 法虽然能够应用于量测岩石内部变形场, 但天然岩石结构复杂, 每一个用于实验量测的岩石样品结构差异性很大, 难以保证被测岩石 RVE 结构的一致性以及所获得的应变场具有足够代表性。同时, 由于 DVC 法要求被测岩石 RVE 内部必须有满足计算要求的高质量散斑^[119], 而很多类别岩石内部并不存在这样的散斑, 这使得 DVC 法难以直接应用于测量此类岩石的内部变形场。为解决此难题, 笔者采用多材料 3D 打印技术制备了内置散斑载体与裂隙结构的三维透明模型(图 21), 发展了三维散斑数字图像相关法, 获得并定量分析了含裂隙模型的内部变形场, 为透明定量解析三维非连续结构内部变形分布演化特征与变形破坏机理提供了新方法和新途径。

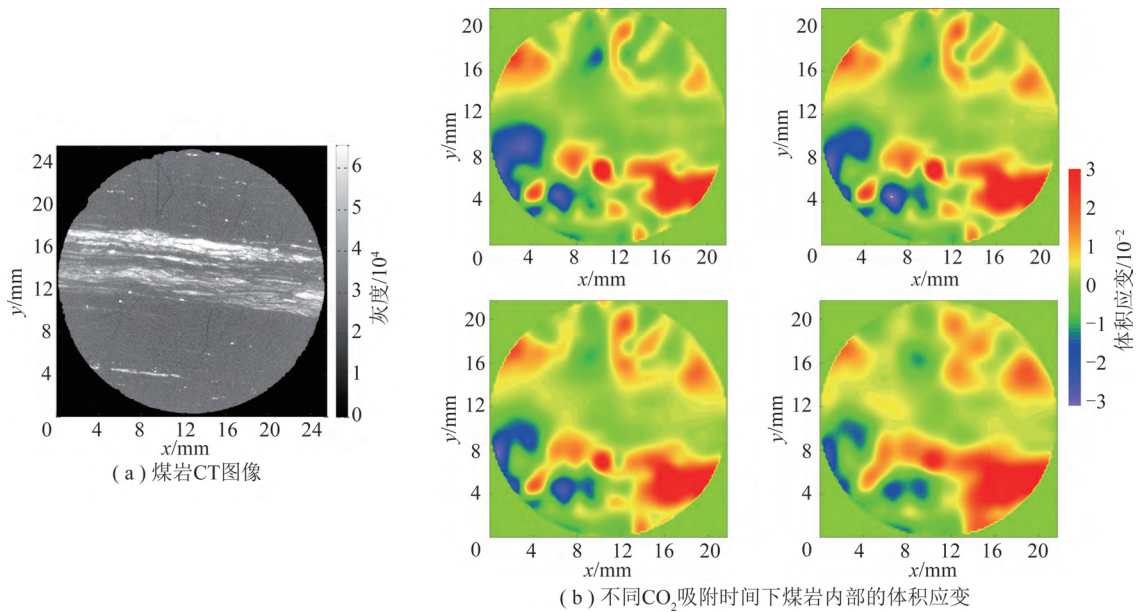


图 20 不同 CO₂ 吸附时间下煤岩内部的体积应变^[116]

Fig.20 Volumetric strain inside a coal at different CO₂ sorption time^[116]

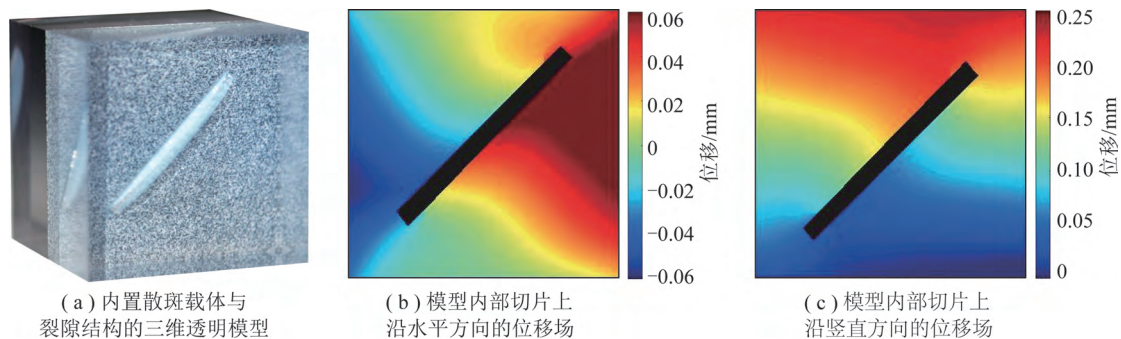


图 21 内嵌裂纹模型位移场的透明解析

Fig.21 Transparentized solution to the displacement field of a 3D fractured model

7 岩石内部渗流场的透明解析

准确认识和定量表征岩石内流体输运行为对于研究和解决煤与瓦斯共采、油气资源开发、土壤污染

物运移、CO₂地质封存及核废料处置等一系列工程问题具有重要意义^[120-122]。然而, 目前常用的 RVE 尺度岩心驱替实验重点关注流体宏观输运性质, 如渗透率、相渗曲线和毛细压力曲线等特征, 缺乏对这些宏

观输运性质演变起控制作用的孔尺度流体运移机理的深入分析和准确描述,导致宏观输运性质演化规律难以预测。同时,由于岩心驱替实验中岩石内部流体流动过程不可见,且孔隙结构存在显著非均质性,全场流动模式极为复杂,仅凭宏观认识难以准确反映和描述真实流动规律。常用的微观模型实验在模型制备及施加温度压力条件等方面受限,且模型一般为小尺度二维模型,导致微观模型实验结果难以直接应用于实际工程。此外,常用的流体动力学计算方法(CFD)在处理复杂几何结构及多相渗流行为受到较大限制,且受限于计算资源,模拟计算难以准确反映真实地层非均质性孔隙结构内的多相输运行为。针对常规岩心实验、微观模型实验及传统数值分析存在的问题,笔者借助 3D 打印技术、自主设计研发的原位三轴加载 CT 成像系统^[49-51](图 22)以及改进的并行格子玻尔兹曼方法(LBM),透明显示和定量解析了复杂岩石复杂结构内流体输运行为及非均质孔隙结构中的非混相界面不稳定性^[123],探讨了复杂孔隙系统内非混相水油驱替动力学特征、优势路径及其对孔隙结构几何参数^[124-125]、流体黏度等物理参数^[126]的敏感性,通过直观展示流场、识别和分析孔隙结构内流体流动路径,阐释了岩石复杂结构内流体输运控制机理。这些研究为揭示岩石复杂结构内流体渗流机制及定量分析流体宏观输运特性、解决实际问题提供了基础和手段。

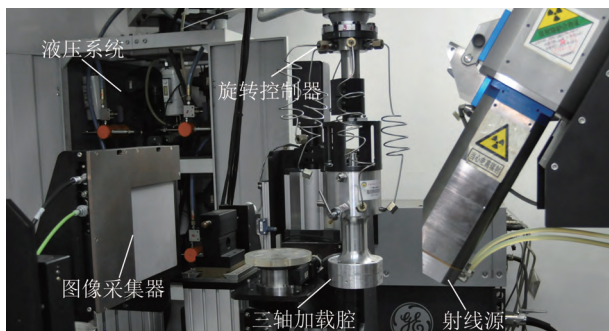


图 22 自主设计研发的原位三轴加载 CT 成像系统

Fig.22 Self-developed in-situ triaxial loading and CT imaging system

针对长期注水开发老油田含水率大幅上升、储层水窜导致采收率下降、注水无效循环以及废水处理成本升高等工程难题,笔者采用高精度微米 CT 成像方法,获得了真实储层不同水驱条带代表性三维孔隙结构,依据天然岩石真实结构信息,采用 3D 打印技术制备了岩石孔隙结构的透明模型,利用透明模型的多相驱替实验,直观展示和定量解析了油、水、堵剂、聚合物、表面活性剂驱替过程(图 23),揭示了条带结构渗透率级差及注入黏度差异是高渗透条带形成水窜

通道主要原因,堵剂运移路径及原位成胶是保证后续注入转向进入驱替高含油区域、进而提高剩余油采收率的重要因素^[126]。

油气注液驱替开采会造成储层地应力重分布,引发岩石结构变形,进而改变岩石内流体的驱替特性。然而,储层岩石深埋地下,驱替开采引发的岩石孔隙结构三维形变及驱替行为“看不见、摸不着”,难以直观显示和定量描述,同时也缺乏三维孔隙变形过程中孔尺度非混相驱替动力学行为与机理的科学认知与理论解析模型,传统实验方法无法观测孔隙变形时的三维非混相驱替行为演化,难以揭示驱替过程的主控因素^[127-129]。为解决该问题,笔者在天然岩石三维孔隙结构 CT 图像的基础上,采用 3D 打印技术,制备了与天然岩石相同孔隙结构的三维物理模型(图 24,其中, P^* 为归一化的围压; E_{R2} 为驱替效率),采用自主研发的原位三轴加载 CT 成像系统^[49-51],开展了不同围压条件下三维孔隙结构变形与变形孔隙结构内三维油水驱替演化的原位 CT 扫描实验^[131],透明显示并定量分析了不同围压条件下油水驱替过程中驱替前缘运移行为及指进现象、优势路径以及残余油空间分布的动态演化(图 23),建立了有效应力、孔隙变形特征以及油水驱替效率之间的定量关系,为科学认知和定量描述油气资源开采引起的储层岩石孔隙结构形变与水油驱替机理提供了新手段、新方法,取得了新发现。

直接观测与定量表征煤层开采过程中煤岩内部三维裂隙网络演化以及裂隙网络内部流体流动是预测导水裂隙带演化和防治矿井水污染的重要基础。然而,采动应力作用下煤岩内部三维裂隙网络发育演化以及流体流动难以直接观测,现有理论模型和数值模拟方法难以计算和预测这一复杂过程。近年来,国内外学者尝试使用 CT 成像技术来研究岩石内部三维裂隙演化与流体流动规律^[132-134],但受限于实验设备和测试方法,目前研究大多采用对变形破坏后的岩石样品进行 CT 扫描来观测岩石内部的三维裂隙网络及流体分布。然而,这种方法难以观测样品在承载条件下的内部结构变形与流动行为,相较于原位应力状态下三维裂隙结构和流体流动行为会产生较大误差。针对上述挑战,笔者利用所研发的原位三轴加载 CT 成像系统^[49-51],开展了不同开采应力路径下煤岩三维裂隙网络演化与水流特征的原位 CT 观测实验,直观展现并定量表征了不同应力阶段煤岩内部三维裂隙网络的拓扑结构、连通性和裂隙生长闭合,并分析了其对裂隙煤岩渗透率的影响(图 25, C 为连通性系数),该研究提供

了一种直接观测和定量表征采动应力下煤岩三维裂隙网络演化和渗透率改变的实验方法,为预测煤

矿开采过程中导水裂隙带的分布与演化以及矿井水污染防治提供了基础和参考。

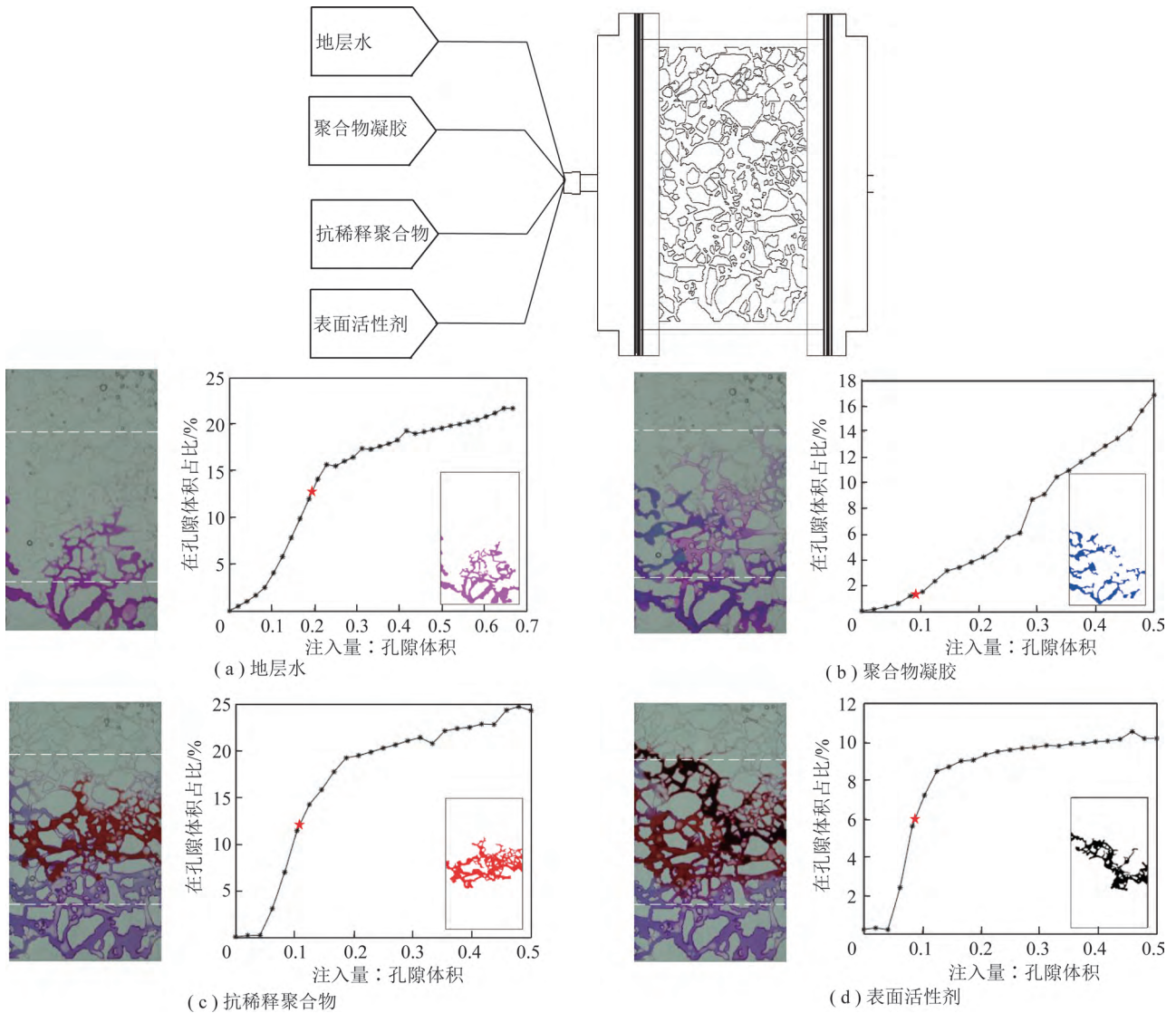


图 23 高中低渗非均质孔隙结构内调剖堵水透明可视化实验^[126]

Fig.23 Visualization of water flooding, polymer gel injection, antilution polymer flooding, and surfactant agent flooding processes in a 3D printed heterogeneous porous model^[126]

值得关注的是,煤炭资源开发过程诱发的岩石灾变常常是固体变形与流体流动耦合作用的结果,如何透明显示和定量解析岩石灾变中的流固耦合效应一直是岩石力学研究的前沿课题。基于作者建立的固体应力场透明解析方法以及流体双折射法^[136-140],笔者制备了内含流体介质的岩石复杂结构的3D打印模型(图6(b)),提出灾变过程中岩石固体与流体应力场耦合作用的透明解析方法。该方法同时捕捉外载作用下岩石模型固体和流体内部的应力光弹条纹(图26),利用作者改进的光弹条纹解析方法,提取固体和流体介质的应力场,实现岩石变形过程中内部固体与流体应力场耦合作用及致灾机理的透明解析。其中流体双折射

法(Flow-Induced Birefringence, FIB)是指利用具有双折射效应的流体来直观显示流场应力分布的方法,例如,PHILIPPOFF^[136],PRADOS和PEEBLES^[137]等学者研究发现了流体的应力双折射效应;MULLER和VERGNES^[138]研究了流体应力双折射条纹与流体内部应力场的对应关系;SENGUPTA等^[139]利用流体应力双折射条纹研究了圆柱绕流条件下流体内部的应力场演化(图27);AUHL等^[140]借助流体双折射条纹分析了不同应变率条件下流体流动过程中的应力场,并与数值计算结果进行了对比(图28,其中, ϵ_c 为应变率; τ_b 为时间)。上述研究为透明解析岩石内部流体介质与固体结构内部应力场耦合效应提供了途径和方法。

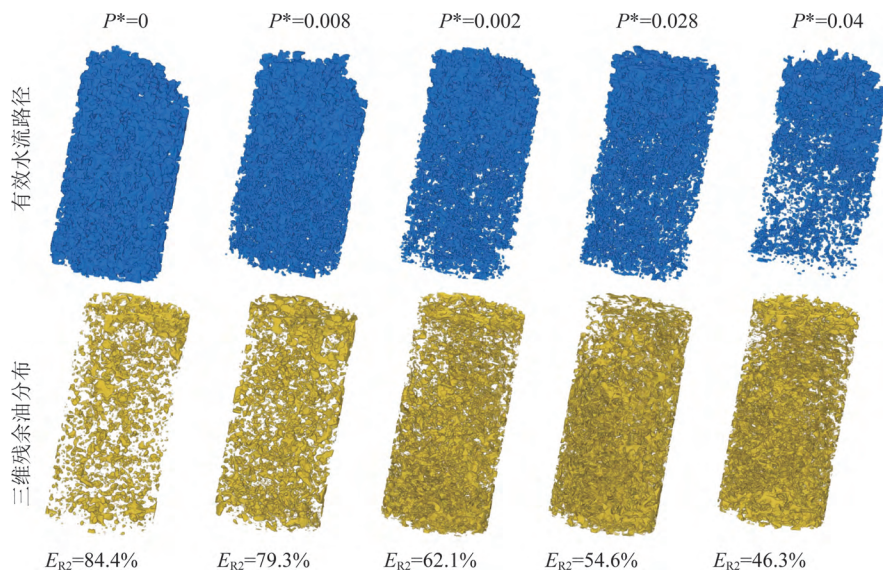


图 24 不同围压条件下水驱路径与残余油空间分布^[131]

Fig.24 Water flow paths and 3D oil trapping under various confining pressures^[131]

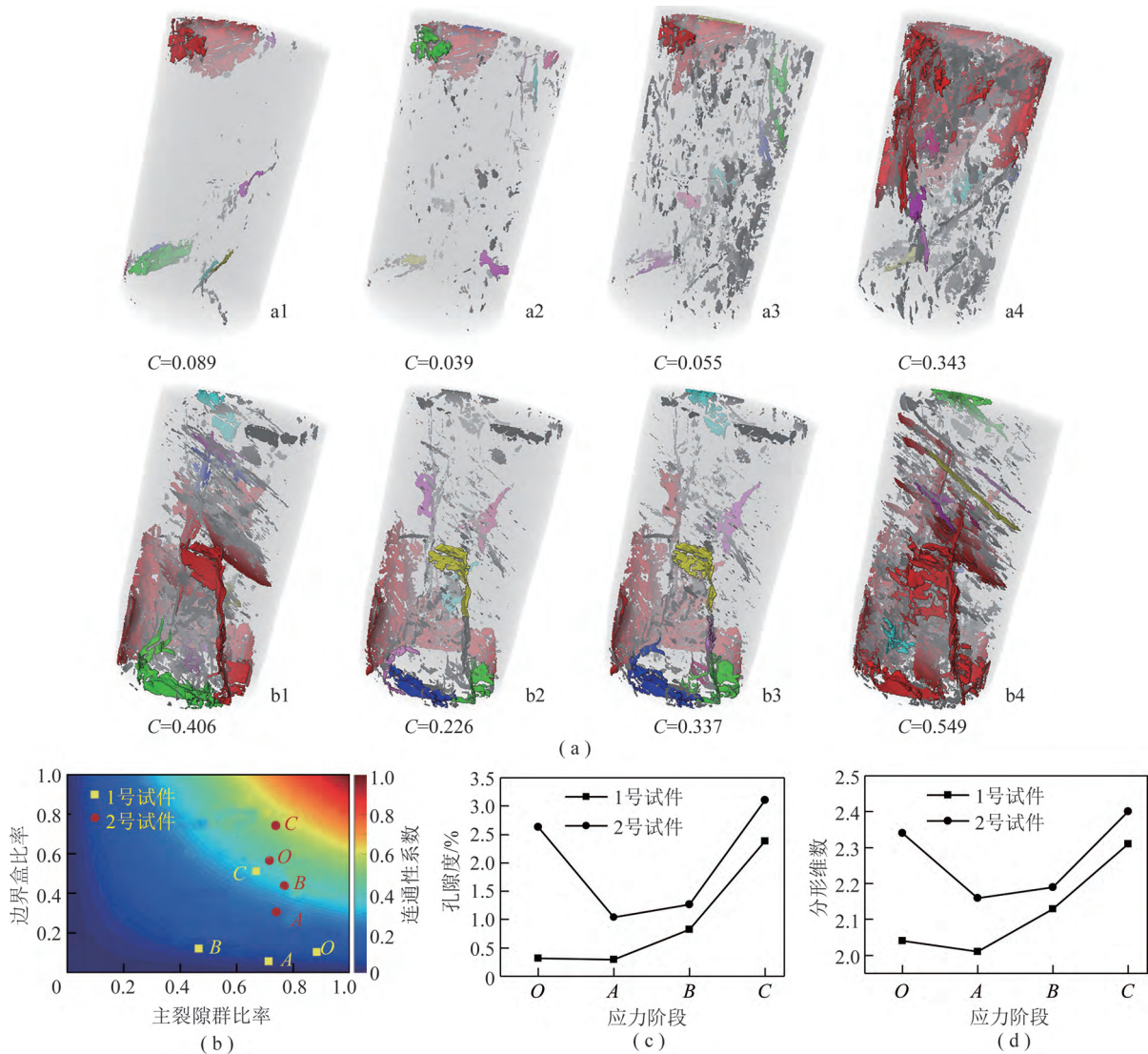


图 25 不同开采应力路径下煤岩内部三维裂隙演化特征^[135]

Fig.25 Evolution of 3D fractures inside a coal under various mining-induced stresses^[135]

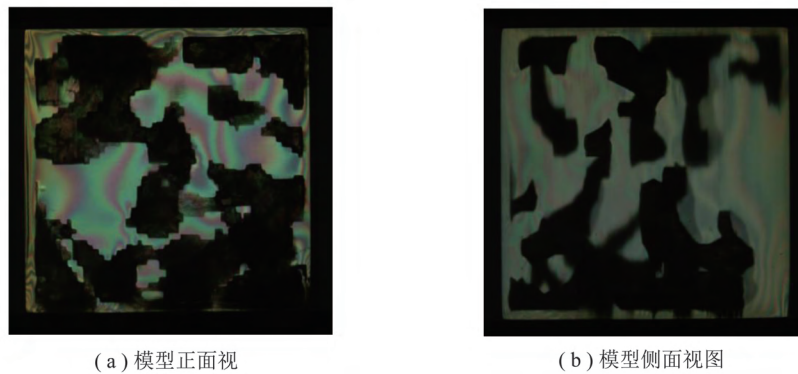


图 26 竖向压缩时内含流体介质的三维孔隙结构固体与流体应力条纹

Fig.26 Stress patterns of the solid and liquid in a 3D porous model under vertical compressive loads

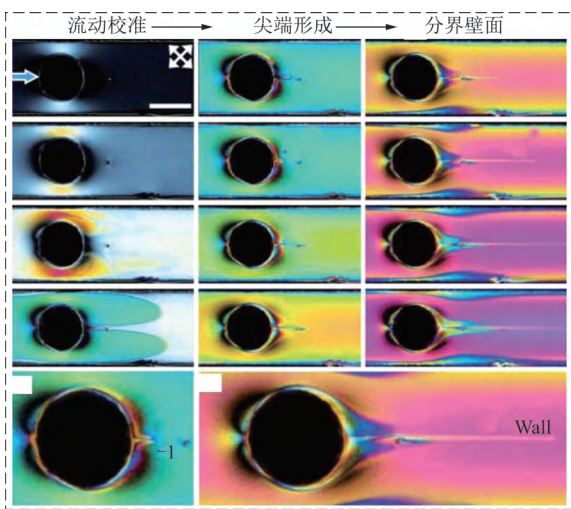


图 27 流体绕过圆柱障碍物时的流动情况^[139]

Fig.27 Fluid birefringence fringe during fluid flow through one cylinder^[139]

$\dot{\epsilon}_0/s^{-1}$	HDPE1 155 °C $\tau_0=5.61$ s	HDPE2 155 °C $\tau_0=14.8$ s	HDPE3 155 °C $\tau_0=28.0$ s
0.35			
0.70			
1.74			
3.48			
6.95			

图 28 不同应变率下流体内部应力实测值与数值结果的对比^[140]

Fig.28 Comparison of fluid birefringence fringes and numerical solutions under different strain rates^[140]

8 结论与展望

(1) 三维数字重构方法可以经济有效地获取和透明显示岩石内部非连续结构,但目前研究主要集中在利用有限微观结构信息进行岩石 RVE 模型重构,在重构模型尺度、重构效率和模型精度方面仍需要进一步提升。

(2) 3D 打印技术为制备岩石复杂非连续结构物理模型并量化非连续结构对岩石灾变力学行为的影响提供了新途径。但研制反映天然岩石物性并能够透明量化岩石多物理场行为的 3D 打印材料仍面临诸多挑战,尚需从多方面进一步研究和改性现有的打印材料。

(3) 基于具有自主知识产权的原位三轴加载 CT 成像系统、三维数字重构方法及研制的透明 3D 打印材料,制备了具有与天然岩石一致非连续裂隙、孔隙结构及相近物理力学性质的岩石透明物理模型,为通过 RVE 物理模型揭示并量化岩石灾变的内部非连续结构及多物理场耦合效应创造了条件。

(4) 初步形成了岩石非连续结构应力场、应变场、渗流场等多物理场定量透明解析理论与方法,为破解开采诱发的岩石灾变“黑箱”机理、建立基于 RVE 尺度多物理场透明解析的非连续岩石力学与灾变分析理论、实现开采灾害的透明推演、超前预警和科学防控提供了途径和研究基础。

需要指出的是,岩石灾变内部非连续结构及多物理场效应的透明解析与透明推演研究尚属刚刚起步,当前研究面临诸多挑战。例如,除需进一步研发反映天然岩石物性并能够透明量化岩石多物理场行为的 3D 打印材料外,在透明解析岩石内部塑性变形与应力场特征、建立内部塑性变形解析量与宏观塑性力学响应之间的定量关系、透明解析多物理场之间的耦合效应、分析和量化多相(固、液、气)多物理场之间的

相互作用仍存在困难,迫切需要通过多学科交叉融合开展更深入的研究。

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