• 自然灾害防治面临的挑战与应对 •
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强震地质灾害机理与预测面临的挑战与应对*

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[摘 要] 强震是诱发山区地质灾害的重要因素之一,严重威胁人民生命财产安全、经济社会高质量发展和国家重大工程建设。随着国家重大工程的实施和城镇建设的快速发展,加之气候变化的影响,地震和极端气候诱发地质灾害的风险显著加剧。然而,目前仍缺乏对强震地质灾害链生演化机理和风险防控技术方法体系的系统研究。本文梳理了同震滑坡启动机理与易发性预测、震后地质灾害链演化机制与预测、强震地质灾害长期效应方面的国内外研究进展,提出"跨时空尺度的强震灾害链生演化规律与全过程动力学机理"和"数据与机理联合驱动的强震地质灾害风险预测"两个关键科学与技术问题。建议从地球系统科学角度出发,研究构造内动力和气候变化外动力对浅表层岩石圈层的影响,探究构造—气候—地貌相互作用下的地质灾害孕灾背景,建立长时序强震地质灾害数据库,揭示强震地质灾害时空演化规律;揭示斜坡地震动响应规律和跨尺度、多相多场、多因素耦合作用下的强震灾害链级联演化机理;发展基于动力学机理、人工智能与高性能计算深度融合的灾害链风险模拟预测新范式;通过多学科交叉和多部门联动,健全强震地质灾害应急响应和风险防控体系,支撑高效科学的国家自然灾害防治体系建设,为世界强震地质灾害研究与防控提供中国案例。

[关键词] 强震地质灾害;灾害链生机理;监测预警;危险性预测;自然灾害防治体系

我国是世界上地震灾害风险最高的国家之一。自20世纪以来,全球约1/3的陆上破坏性地震发生在中国,七度及以上地震高烈度区占国土面积的58%(《中国地震动参数区划图》),地震造成的死亡人数占到了全球地震总死亡人数的近1/2(《国家防震减灾规划(2006—2020年)》)。除了直接伤亡和损失外,地震诱发的次生地质灾害是加剧地震风险的关键因素,其所造成的损失有时甚至超过地震本身[1],对震区人民生命安全和重大基础设施构成严重威胁。

近二十年来我国强震频发,平均每年发生3次6级以上强震,累计已发生了6次7级以上强震,特别是在青藏高原及其周缘地区,相继发生了2008年汶川8.0级地震、2013年芦山7.0级地震、2014年鲁甸6.5级地震、2017年九寨沟7.0级地震、2022年芦山6.1级地震、2022年泸定6.8级地震、2025年定日6.8级地震等多次强震事件[2-8]。其中,2008年汶川地震是迄今为止全球单次地震诱发地质灾害数量最多的地震,诱发了超过20万处地质灾害,直接导致了约2万人遇难[9]。强震地质灾害具有影响范围广、危害大、灾害链长期效应显著等特点。例如,地震诱发同震滑坡(即强烈地震动作用下岩土体失稳引发的斜坡破坏,集中发生于震后数秒至数分钟内)可能堵塞河流,形成滑坡坝—堰塞湖—溃决洪水灾害链[10];同震滑坡产生的堆积体可能在震后降雨作用下复活并形成泥石流灾害链[11];震裂山体可能演变为震后新生滑坡灾害链[12]。这些灾害不仅严重影响震后重建恢复和经济社会可持续发展,也对震后物质运移、地貌演化和生态功能产生长期影响[13]。随着地震高烈度山区国家重大工程的实施与城镇建设的快速发展,加之近年来气候变化

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Fan XM, Dai LX, Wang X, et al. Challenges and responses in the mechanisms and prediction of strong-earthquake-triggered geological hazards. Bulletin of National Natural Science Foundation of China, 2025, 39(6): 1016–1029. (in Chinese)

导致的极端天气事件频发,地震和极端气候诱发地质灾害风险显著加剧。因此,深入研究强震地质灾害链生机理与防控技术,对提升我国应对强震地质灾害风险的能力至关重要。

强震地质灾害机理与预测是国际前沿科学问题,其难点在于强震地质灾害的成灾过程与链生机理是随时间和空间动态演化的,可以分为同震响应、震后效应和长期效应三个阶段(图1和图2)。针对同震响应,国内外学者对不同地震案例开展了大量研究,虽然初步揭示了地震诱发广域地质灾害的空间分布规律和大型滑坡启动机理,但目前还缺乏对断层破裂过程—斜坡地震动响应规律—同震滑坡启动机理—区域风险预测的系统性认识和耦合模型;针对震后效应,现有研究主要聚焦震后泥石流机理与数值模拟,缺乏对震后滑坡—泥石流灾害链启动—运动—致灾全过程动力学机理、模拟预测与精准预警方面的深入研究;针对长期效应,强震所产生的震裂山体的长期损伤裂化,对山区物质运移和地貌演化的长期影响,以及对生态系统的扰动与恢复,均在一定程度上重塑了震区的地质环境条件,构成了未来灾害发生的本底背景,但这方面的研究目前还十分薄弱。因此,开展跨时空尺度的强震地质灾害全生命周期链生演化机理与风险预测研究,深入认识不同演化阶段灾害的动力学机理,探索数据与机理耦合驱动的强震地质灾害风险预测模型,不仅对提升我国应对强震灾害风险的能力具有重要支撑作用,也可以为全球强震地质灾害防控提供科学借鉴。

1　强震地质灾害研究现状

1.1　同震滑坡启动机理与易发性预测

一次强震可触发数以万计的同震滑坡[14]。地震如何触发大型滑坡,如何快速评价同震地质灾害影响范围,是同震地质灾害研究的两个关键问题,对应急救援和临时安置点的安全评估至关重要。现有研究主要聚焦同震滑坡空间分布规律、基于野外观测与振动台物理模型试验的斜坡地震动响应规律、滑坡启动机理和同震滑坡易发性预测模型构建。

1.1.1　全球同震滑坡数据库

同震滑坡数据库是揭示滑坡空间分布规律和控制因素、建立易发性预测模型的基础。早期同震滑坡编目

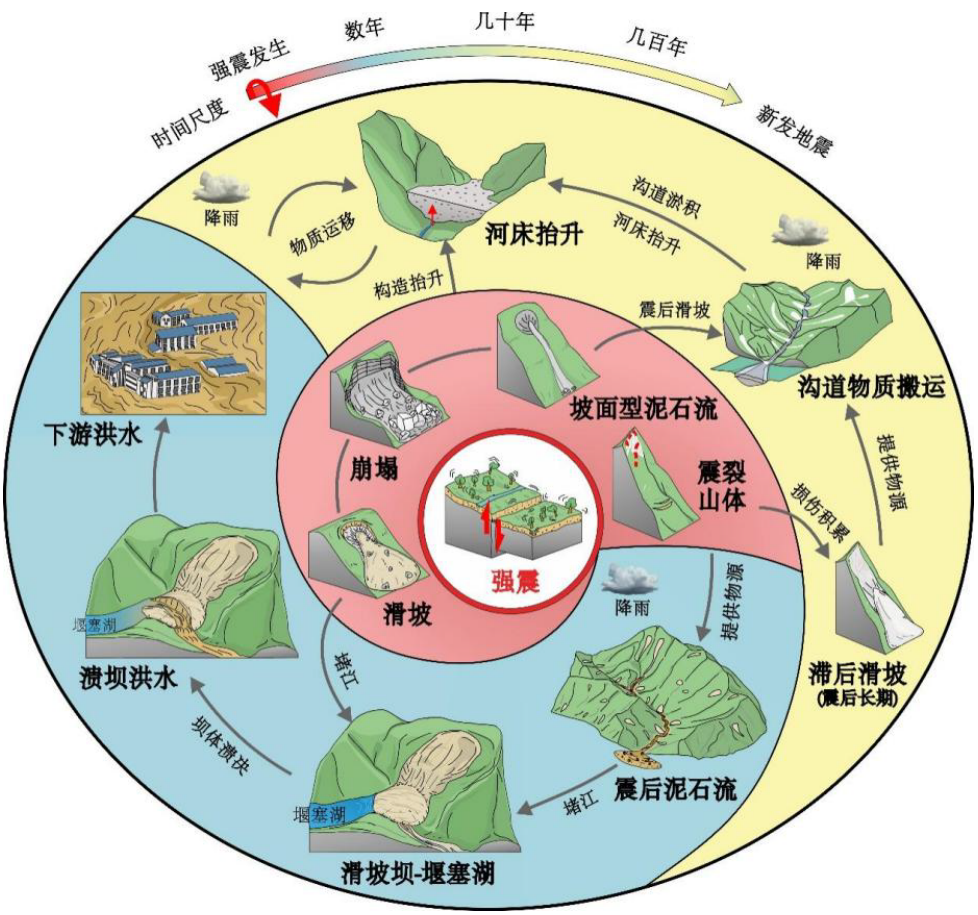

图1　强震地质灾害链生演化示意图(红色代表同震响应阶段,蓝色代表震后效应阶段,黄色代表长期效应阶段)

Fig.1　Schematic Diagram of the Evolution of Strong Earthquake-triggered Geohazard Chains (Red:Coseismic Response Stage;Blue:Post-seismic Effect Stage;Yellow:Long-term Effect Stage)

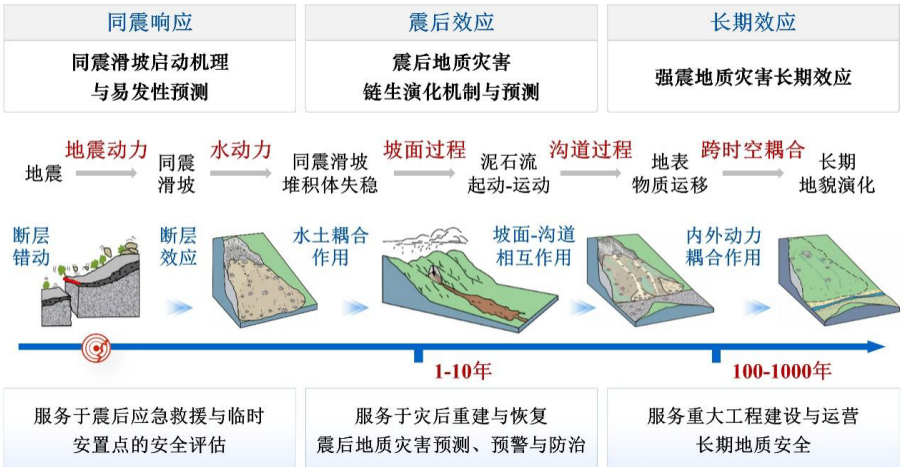

图2 强震地质灾害机理与预测研究思路

Fig.2 Conceptual Framework for the Study of Mechanisms and Prediction of Strong Earthquake-triggered Geological Hazards

的研究多聚焦单一地震事件[15]，国内外学者相继建立了具有代表性的事件型数据库[9,16-19]。然而，受限于遥感数据匮乏、影像时空分辨率较低、解译标准不统一等因素的影响，基于不同震例的滑坡数据难以实现系统性对比研究，制约了对同震滑坡普适性发育分布规律的认识[20]。美国地质调查局(United States Geological Survey，USGS)于2017年通过整合多次地震事件建立了全球同震滑坡与液化数据库[21]，初步形成跨震例资料框架。但该数据库的滑坡记录点面混杂，空间精度差异较大，难以满足滑坡规律研究与机器学习模型的训练需求[22]。因此，构建空间覆盖广域化、质量控制标准化、结构规范统一化的大尺度数据库，已成为该领域亟待突破的基础性科学目标。近年来，遥感技术与人工智能算法的发展共同驱动了区域性滑坡精准识别与编目构建的标准化进程[23]。例如，据此构建的全球同震滑坡数据库，系统收录了1970年以来38次强震事件诱发的近40万条滑坡记录，覆盖了全球主要地震构造带与气候区[24]。此类数据库的建立，通过提供高置信度全球样本库，标志着该领域研究正式迈入“标准化数据驱动”的新范式，为同震滑坡的前沿理论研究和智能预测技术提供了有力支撑。

然而，现有数据库仍存在局限：一是部分地震动参数来源不一、精度存在差异，导致因子一致性和模型输入可靠性一定程度上受限；二是滑坡的高精度区分和体积估算等仍依赖人工干预，缺乏自动化的高效处理方法。未来应结合高时空分辨率遥感观测、地震动模拟反演与智能识别算法，建设动态更新的同震滑坡数据库体系，以实现从“静态编目”向“动态表征”的跨越。

1.1.2 同震滑坡启动机理

同震滑坡的启动机理具有多尺度多因素耦合的复杂特征，是强震地质灾害风险评估与科学防灾的理论基石。随着地球物理监测手段的不断提升、物理模型试验技术的进步以及数值模拟方法的发展，通过现场原位观测、遥感解译、大型振动台试验、数值模拟等方法，学界对斜坡地震动响应规律和同震滑坡启动机理有了更深入的认识，取得了系列进展，并总结出了共性规律认识[13,25]。当前研究聚焦三个核心方面：地震动传播与放大效应、斜坡动力响应规律以及岩土体震裂损伤演化机制[4,26-30]。

基于同震滑坡空间分布规律研究发现了显著的“地形放大效应”(同震滑坡倾向于发育在坡体中上部)、“坡向效应”(同震滑坡在背坡向发育更为密集)和“断层效应”(在距离断层5 km范围内、逆冲断层上盘，滑坡集中发育)。为了揭示这些效应背后的物理力学机制，现有研究开展了大量振动台实验与数值模拟，揭示了斜坡放大效应可显著改变边坡的动力响应特征与破坏模式[31-37]。尤其，在断层错动等复杂构造背景下，斜坡放大效应更加显著，更易诱发大型滑坡[38]。在震裂损伤演化机制方面，近年来的研究聚焦地震荷载作用下岩土体内部裂隙扩展、微观损伤累积及其对抗剪强度的削弱效应。通过岩土动力学试验与多场耦合数值分析，进一步揭示了滑坡由潜在不稳定向失稳破坏转化的细观过程，加深了对震裂损伤机制和斜坡失稳机理的认识[39-42]。

综上所述，同震滑坡启动机理研究尽管取得了显著进展，但仍面临诸多挑战，如地震动输入边界条件不确定性、复杂地形与三维地质模型参数获取的不足，限制了对复杂地质条件下真实边坡三维动力响应与启动机理的深入研究。未来亟需结合高精度地质与地球物理探测技术，并加强多源监测数据的融合应用，以提升对同震滑坡启动机理的科学认知与工程适用性。

1.1.3 同震滑坡发育分布规律与易发性预测

同震滑坡的空间发育分布受到地震动参数、地形地貌、地质结构、水文环境等多因素的耦合影响[14]。早期研究主要通过统计分析与经验模型,在典型震例中建立了滑坡分布与主控因子的区域性关联[43,44]。然而,此类规律总结大多依赖局地样本训练,缺乏对不同构造带和气候区的应用普适性,难以满足跨区域风险评估的需求[45]。随着高分辨率滑坡编目与多源环境因子数据的积累,研究逐步转向大样本驱动的多因子耦合机制解析[46-48]。诸多对不同地震事件的研究表明,地面峰值加速度(Peak Ground Acceleration,PGA)、坡度、岩性对同震滑坡分布具有控制作用[49-52]。然而,不同区域的不同地震事件,受区域特殊地质环境条件的影响,滑坡发生机制与控制因素有时差异较大,如1920年海原地震和2023年积石山地震等发生在黄土地区的事件[53,54]、2002年迪纳利地震和2017年米林地震等发生在冰冻圈区域的事件[55-57]、2018年北海道地震等发生在火山口附近的事件等[58]。

总体来看,现有研究已揭示出同震滑坡空间分布的若干共性规律:在全球尺度,其高发区普遍集中于地震动强烈区、坡度较大与地层抗剪强度较低的地带;在区域尺度,地貌结构与地层组合特征则对滑坡密度与形态差异起决定性调控作用。未来研究趋势正从经验统计向物理—数据融合的过程刻画转变,着力在多源数据约束下实现滑坡分布的可解释性预测。

在同震滑坡预测模型构建领域,开展同震滑坡易发性预测,评估容易发生地震或者可能诱发滑坡的区域。深度学习技术的发展推动了传统滑坡预测经验模型向跨区域智能模型的转变[59-62]。例如,通过多尺度全卷积神经网络架构,模型可自适应提取不同空间分辨率下的地貌形态特征与非线性耦合关系,结合通道—空间注意力机制与跳跃连接结构,显著提升对滑坡主控因子复杂空间关联的建模能力。通过对全球同震滑坡数据库的系统有效训练,模型能够展现出优异的跨构造—气候区泛化性能。为进一步协调区域适应性与广域普适性,已有研究提出“区域—全球”双轨建模策略:在样本充足区(如赤道带、温带等)采用区域模型实现高精度预测;在数据稀缺的地区则启用全局模型进行泛化补偿,确保模型在全球不同地震带—气候区情境下的鲁棒性与稳定运行[24]。

综上所述,当前同震滑坡预测正由震例驱动的经验建模迈向基于机理约束与数据融合的智能化演进阶段,研究正朝着跨区泛化、物理可解释与快速响应的方向发展,显示出由“事件复现”向“前瞻预测”转变的明显趋势。

1.2 震后地质灾害链生演化机制与预测

震后山区地质环境发生剧变,同震滑坡产生的大量松散物质在震后降雨作用下复活形成滑坡,并为泥石流提供丰富的物源,导致震后泥石流活动性和规模均较震前大大加强。此外,震松震裂的山体随时间可能不断劣化,在震后产生新生滑坡(图1)。然而,由于缺乏对震后地质灾害链生演化机制的认识和预测模型,导致震后灾害规模被大大低估,造成治理工程屡治屡毁。汶川震后国内外学者开始关注震后地质灾害机制与预测研究,在震后地质灾害时空演化规律、链生机制、危险性预测和泥石流预警方面取得了重要进展。

1.2.1 震后地质灾害时空演化规律与链生机制

国内外学者基于全球多次强震的震后长时序地质灾害数据库研究,量化了震后滑坡规模—频率动态演化关系,发现震后滑坡频率较震前先大幅增加,而后在十年内呈幂律衰减到震前水平的普适性规律[13,63,64]。现有研究通过室内水槽和数值模拟试验表明,震后滑坡频率快速衰减主要源于堆积体物理力学性质的时效性变化。这一过程被定义为震后堆积体的“自愈机制”[13,65],即堆积体受到颗粒粗化(细颗粒流失导致渗透系数增大、黏滞系数降低)[66-69]和植被恢复(冠层截留降雨、根系调控渗流路径及浅层加筋)的控制[70-74],导致其稳定性随时间增强,发生启动并转化为泥石流的降雨阈值随时间增大。震后泥石流的启动机制也随时间发生明显的变化,从最初的“坡面—沟道物源联合启动型”逐渐转化为“沟道物源径流侵蚀型”[75,76],主要受控于同震滑坡堆积体的规模、物质组成及沟道连通性[77,78]。由于震后沟道内仍存有大量物源,因此泥石流的活跃周期较滑坡更长,且受降雨影响存在较大的波动性[79]。

另一方面,地震造成岩体震松震裂,一些坡体在震后的“自愈过程”中逐渐趋于稳定,但大部分坡体力学性质会随时间不断劣化,致使斜坡发生滞后性破坏。例如,2017年新磨村滑坡就是1933年叠溪震后效应所导致[64,80]。然而,针对岩体震裂损伤/愈合过程、机制与量化评价方面的研究相对较少[81],部分研究通过地震波速度反演弹性模量演化,揭示岩土体介质经历的震裂损伤及其愈合过程[82,83]。因此,当前研究亟需深化对不同类型震后地质灾害演化过程和机制的认识,开展长周期野外观测,揭示斜坡岩土体的“自愈”与“裂化”的控制因素和机制,从而为震后地质灾害风险防控提供理论支撑。

1.2.2 震后滑坡危险性预测

震后滑坡危险性预测主要是在认识滑坡时空演化

规律的基础上建立模型,结合致灾因子强度(如地震动力、降雨量)预测未来滑坡发展趋势(如发生滑坡的时间、密度、频次等)。现有研究通过建立震后滑坡灾害多期数据库,分析其与地质环境因子的时空关联性,采用经验统计、物理力学模型与数据驱动智能模型等方法建立危险性预测模型[84,85]。传统经验统计模型仅能考虑滑坡的静态易发性,难以考虑地质环境因子随时间的动态变化影响,因此难以预测震后滑坡的动态危险性[86]。极少数研究考虑了震后滑坡控制因素的动态变化,定量刻画了震后滑坡的动态变化[75]。物理力学模型主要采用无限边坡法,其缺点在于极大地简化了岩土体物理力学性质(大多根据岩性和土性确定抗剪强度参数经验值),假设的滑体厚度常常与实际有极大出入,难以应用于大区域范围[87],导致该方法结果不确定性较大。此外,该类模型也很难定量刻画震后物源特征和力学参数的动态变化,无法考虑前述的颗粒粗化、植被效应等对震后滑坡稳定性的影响。近期不少研究转向数据驱动的机器学习模型,通过整合震后松散堆积体的特殊物源条件与剧变成灾环境特征,选取地震动力、同震物源、地形地貌及水文要素的组合变量,采用信息增益检验优化因子权重,并基于随机森林算法构建评价模型,从而实现震后滑坡危险性预测[75]。然而,机器学习模型主要依赖输入—输出模式映射,对地质环境因子间的复杂非线性关系虽有较强学习能力,但缺乏对灾害形成过程的物理约束与机理解释,因此在跨震例与跨区域推广时泛化性能仍有待提高。因此,亟需加强震后地质环境的多维度监测,获取高时空分辨率的地质环境基础数据,以突破两类模型的认知瓶颈。未来研究可通过融合机理模型提供的约束条件与机器学习的模式识别优势,提升模型的可解释性与普适性。

1.2.3 *震后泥石流监测预警与模拟预测*

震后泥石流具有突发性、群发性、极强的侵蚀放大效应。例如,汶川地震后2010年“8·13”三大片区特大泥石流事件,在映秀、龙池、清平等地爆发群发性泥石流,出现“沟沟吹喇叭,逢沟必发”的现象[88-90],对灾后重建城镇造成巨大威胁。震后泥石流监测预警和基于数值模拟的危险性评价预测,评估泥石流的规模、影响范围及运动特征等,对灾害防控和恢复重建至关重要[91,92]。

传统泥石流的I-R(降雨强度—历时)和I-D(雨强度—前期降雨量)预警模型多采用静态单一降雨阈值,而震后泥石流降雨阈值受到坡面和沟道物源演化的影响呈动态变化,导致大量漏报和误报[74,93]。现有研究基于大量野外监测站获取的震后泥石流和雨量数据,发现了汶川地震和台湾集集地震后,降雨阈值先降低而后随时间逐渐回升的规律[13]。这种变化实际上也是受控于震后滑坡堆积体物源特征的变化和自愈机制(见1.2.1节)。同时,通过分析降雨参数与泥石流发生之间的关系[79,94],结合数理统计分析和人工智能算法,建立了震后泥石流动态临界雨量阈值模型,量化了临界阈值在震后随时间的变化规律,实现了震后泥石流智能预警,避免了震后泥石流重大人员伤亡[95]。

为进一步提升预测能力,震后泥石流的模拟预测在理论模型与算法架构方面均实现了多层次的发展与突破[96,97]。围绕震后泥石流“起动—运动”动力学过程,考虑流域植被根系对土体结构与强度的影响,在渗流理论、非饱和土力学与水动力学等多学科理论的交叉基础上,发展了适用于震后泥石流物质触发的启动模型[98-100];由最初的单相流提升为固—液两相流运动模型,能够有效描述颗粒与流体间的相互作用,并充分考虑侵蚀夹带、颗粒分选等动力学机制[101-103],进而实现震后泥石流的演进过程重建、情景模拟与预测。在算法架构方面,基于连续介质假设的网格法[104-106]、以离散单元刻画物质行为的离散元法均被广泛应用于不同场景[107,108],连续—离散耦合方法通过整合网格法对流体连续性的描述与离散元法对颗粒离散运动的刻画,兼顾颗粒的离散运动特征与流体的连续性行为,显著提升了模拟精度与适用范围[109-111]。

在上述研究进展背景下,震后泥石流预警与模拟预测仍面临诸多挑战:现有动态降雨阈值模型虽可实现目标流域的预警,但因岩土特性与地表覆被的显著空间分异及泥石流起动可靠数据匮乏,难以跨流域与震例推广;同时,数值模拟研究多聚焦单一演化阶段,且大尺度三维计算存在效率瓶颈。亟需构建“起动—运动—致灾”全链条模拟框架,融合AI与GPU并行计算技术,提升大范围流域高分辨率模拟能力,推进工程实用化。

1.3 强震地质灾害长期效应

强震地质灾害不仅对人居安全和重大工程造成直接威胁,也是塑造地貌、影响地表侵蚀和长期物质运移的重要因素。强震对山区地貌的影响是多个地表过程相互博弈的结果:逆冲断层活动造成地表隆升,是典型的造山运动;然而,地震诱发大量同震滑坡剥蚀山体,是典型的剥蚀过程;同时,同震滑坡产生的物质通过震后滑坡—泥石流和地表径流侵蚀过程逐渐从坡面搬运到流域内沟道,最终从山区进入河流,伴随着显著增加的震后物质输移通量和碳的运移。因此,强震地质灾害影响着造山带的侵蚀、风化和沉积,对流域地质环境、生态环境和地貌演化具有长期效应,是揭示构造运动—风化侵蚀—地貌演化—灾害效应内在联系的关键纽带[112]。

1.3.1 *震后地质灾害物质运移过程与规律*

强震地质灾害全生命周期演化伴随着物质从坡面到流域内沟道再到河流的运移过程,串联了整个流域的灾害级联过程[13]。基于1923年日本关东*M* 7.9地震[113]和1929年新西兰默奇森*M* 7.7地震[114]的震例研究表明,观测获得的震后河道沉积物信号通常在<10年到>50年内消散[115,116]。1999年集集地震后,Hovius等[117]提出了评估地震侵蚀效应的方法步骤,包括:(1)滑坡体积估算侵蚀量;(2)追踪震后物质运移过程;(3)量化河流固体物质响应持续时间;(4)解析物质运移和河流响应的时空异性。此后,从坡面—沟道关联的角度量化震后滑坡物质运移过程,成为理解震后地质灾害孕育背景,认识强震对山区地貌演化作用的新方向[116,118]。2008年汶川地震后,震中多个流域的滑坡物质运移路径、滞留时间和长期河流响应研究取得了重要进展,例如:岷江流域内震后12年的追踪观测显示,超过70%的同震滑坡物质仍滞留在坡面,并逐渐趋于稳定,大约20%的物质滞留在山区沟道,少于10%的物质被搬运到河流[76];震后物质运移过程以大型泥石流为主导过程(占运移总量67%),而细粒物质则主要通过降雨侵蚀进入河道[119];不同震后物质运移方式具有显著的规模—频率分布特征差异,且主要依赖强降雨事件,表现出显著的随机性。因此,需结合滑坡物质—沟道连通性与气候事件综合分析,以预测震后地貌演化[78,84,120]。然而,现有研究不同物质运移方式和过程之间的联系与转化机制认识仍不够深入,缺乏长时间尺度、大空间尺度的震后物质运移与地貌演化评价模型。

1.3.2 *强震地质灾害对山区地貌演化的长期影响*

地震诱发大型滑坡坝堰塞河道,其存活时间可达数千年甚至万年以上,对河流水系的侵蚀—输运—沉积能力产生长期影响,从而在不同时空尺度上影响地貌演化[77,121,122],是研究地震地质灾害长期效应中不容忽视的部分。现有研究指出,通过地貌和沉积学方法可以重建历史地震灾害情景(如1933年叠溪地震)[123],并通过量化大型滑坡坝物质的特定沉积物产率,深化其在不同时间尺度上对山区地貌演化长期影响和机制的认识[124,125]。对于寿命较长(千年以上)的大型古滑坡坝,通常对河流地貌具有双重影响:一方面,上游因堰塞湖库区沉积—河床基准面抬升,抑制河流下切,致使上游坡度降低、输移能力下降;另一方面,坝址处形成的陡峭河道裂点,促使下游侵蚀下切增强[126]。因此,古滑坡坝上下游常具有完全不同的地貌特征,上游河谷宽阔,河道水力坡降小,而下游则为深切峡谷,水力坡降大。除此以外,由于强震后河流沉积速率的大幅上升[13],堰塞湖湖相沉积序列成为了记录震前—同震—震后不同沉积过程的连续地质档案。通过高分辨率粒度—磁化率—地球化学等指标分析,该序列可定量评价震后效应的时空规模与持续时间[127,128],已成为推动地球科学与多学科交叉融合的前沿研究方向之一。

1.3.3 *强震地质灾害对生态系统及碳库循环过程的影响*

地震诱发的地质灾害不仅直接破坏大面积植被覆盖与土壤碳库,显著降低生态系统生产力,还通过震后物质运移过程,影响生态系统有机碳的迁移、转化及储存,其结果促进了河流系统颗粒有机碳的高效运输及埋藏[129-131]。当前研究综合应用多源遥感监测与同位素分析等技术,已获取震后碳通量(如植被生产力、河流碳运输等)的时序观测数据,有力证实了强震地质灾害是扰动陆地碳库的重要驱动力[132]。2008年汶川地震造成区域森林覆盖率下降约0.5%,约3 300平方千米的森林遭到破坏,估算生态系统碳损失达13.6 Tg C,相当于中国年均碳汇的68%[133]。新西兰南阿尔卑斯山脉地震诱发的滑坡事件动员了约8~14 Tg C[134], 而台湾集集地震震后在强降雨作用下引发大规模滑坡,导致约3.9 Tg C被转移至河流系统[135]。震后生态系统恢复过程表现出显著的阶段性、空间异质性与长时滞性特征,相关植被覆盖指数在10~15年内恢复,而生态系统碳库的恢复是缓慢而复杂的过程,受到高程、坡度、坡向、土壤性质与气候条件等多种因子的复合调控[136,137],可能需要百年乃至千年才能重新恢复到震前水平。从地质演化的时间尺度看,强震地质灾害作为构造活跃区有机碳侵蚀的关键驱动力之一,其作用具有双向性:一方面,由其所引发的有机碳埋藏与伴随的硅酸盐风化过程共同促进了大气CO_2的消耗;另一方面,剧烈的山体剥蚀加速了岩石硫化物的氧化,并在物质运移过程中释放土壤和沉积物中的有机碳。这一作用过程深刻影响着岩石圈与大气圈之间的碳交换,是长期调控陆地环境碳储存与释放的关键机制[116,138]。未来需发展耦合地貌演化与碳循环的多尺度模型,融合滑坡物质运移、沉积物输运与有机碳跨圈层迁移过程机制分析,模拟强震扰动下的碳剧变与长期演化趋势。

2 关键科学及技术挑战

新时代西部大开发、“一带一路”等国家战略和一系列超级工程的实施,对我国地震高烈度山区,特别是青藏高原及周缘地区的地质灾害风险防控提出了更高的要求。为了保障人民生命安全、重大工程地质安全和生态地质环境安全,针对强震地质灾害防控,亟需从地球系统科学角度出发,通过多学科交叉,解决核心科学问

题(强震地质灾害在不同时间和空间尺度上如何演化,灾害链启动—运动—致灾全过程的动力学机理是什么)和关键技术问题(如何科学预测未来强震诱发地质灾害的风险)。因此,未来研究应聚焦强震地质灾害链全过程动力学机理的理论创新和不同地震情景的灾害风险快速精准预测技术突破。

2.1 跨时空尺度的强震灾害链生演化规律与全过程动力学机理

强震地质灾害链在空间尺度上涉及区域尺度构造稳定性—流域尺度沟道稳定性—坡体尺度斜坡稳定性—细微观尺度岩土稳定性,在时间尺度上跨越同震响应(分钟—天)—震后效应(数年—数十年)—长期效应(数百年以上)。认识跨时空尺度的强震地质灾害链生演化规律是预测未来强震灾害风险的基础,也是地质灾害领域的科学前沿。目前针对区域尺度同震响应和震后效应的研究较多,但震后长期效应方面的研究相对较少,尚未形成强震灾害链全生命周期演化规律的系统认识。亟需重建历史强震地质灾害记录,通过沉积记录、数字地貌分析、树轮等年代学方法,构建历史强震与地质灾害事件的高分辨率时空映射数据库,揭示灾害链对强震事件的长时序—跨空间尺度响应规律。

灾害链全过程动力机理涉及地震动力作用下斜坡响应规律、岩土体累积损伤、多灾种链生演化、长期物质运移等过程,现有研究缺乏这些过程相互作用机理的系统认识。亟需加强“断层错动—山体破裂—坡体震裂—运动演进—物质运移”的全过程动力学机理研究,揭示复杂条件下斜坡地震动响应与岩体动力损伤机制,深化对大型同震滑坡启动机理的认识;阐明降雨、余震、冻融等多因素叠加损伤累积机制,定量评价震后效应;揭示多场耦合作用下的多灾种转化—多灾链汇聚的物质和能量交换过程与机理,构建灾害链全过程动力学模型与物质运移预测模型,为科学评价强震地质灾害全生命周期、全过程风险预测提供理论基础。

2.2 数据与机理联合驱动的强震地质灾害风险预测模型

强震地质灾害风险预测主要是针对发震断层可能产生不同震级地震诱发地质灾害风险的震前预测和发生地震后利用已知地震动参数预测地质灾害可能产生的影响。地震诱发地质灾害的控制因素复杂且空间分布异质性强,其时空分布的精准预测对于震前防灾减灾规划和震后应急快速响应至关重要。现有评价方法主要包括基于遥感大数据的深度学习模型与基于边坡动力稳定性的物理机制模型:前者能快速生成地质灾害空间概率分布图,但存在物理机制不清、预测结果可解释性差的缺陷;后者虽具有物理力学基础,却因模型过于简化、参数依赖性高、计算效率低而难以满足大范围灾害快速预测的需求。因此,亟待突破的核心技术在于建立数据与机理联合驱动的预测模型,针对震前预测,同时需要结合断层破裂过程模拟,建立地质灾害情景推演模型,实现对于地震动载荷、坡体力学特性、地质环境等多因素耦合作用机制的精准刻画,准确识别地质灾害敏感因子与触发阈值,量化滑坡体积分布规律,解析灾害链式演化机理,进而建立适用于不同构造背景、气候分区及地貌单元的智能预测框架,提升模型的准确性与普适性。

机理与人工智能的融合将通过“机理约束的深度学习”实现。模型以地震动传播和坡体响应等动力学方程为物理约束,引导AI模型学习灾害链的内在规律;同时,深度学习用于地震动场与地质参数的高维反演,为机理模型提供边界与参数支持。通过多尺度分层模拟与高性能计算加速,实现全过程模拟的效率与精度平衡,构建具有物理可解释性和跨尺度泛化能力的强震灾害预测框架。

3 研究展望与发展建议

随着国家综合防灾减灾救灾能力建设标准的持续提升,强震地质灾害机理与风险预测已发展为支撑全球减灾行动和可持续发展目标的重要研究方向之一。从建立高效科学自然灾害防治体系的国家需求出发,提出以下建议(图3):

(1)破解强震地质灾害链生演化机理:聚焦跨时空尺度的强震地质灾害链生演化机理,从地球系统科学角度,研究构造内动力和气候变化外动力对浅表层岩石圈层的影响,探究构造—气候—地貌相互作用下的地质灾害孕灾背景,建立长时序强震地质灾害数据库,揭示强震地质灾害时空演化规律;开展现场观测和物理模型试验研究,通过地球物理探测、斜坡地震动现场观测等手段,揭示不同地貌特征、物质组成、坡体结构的斜坡对不同类型地震波的响应过程与破坏机制;推动强震地质灾害启动机理研究向更宏观(如双台阵协同大型振动台试验)和更微观(如高精度CT扫描)发展,破解跨尺度、多相多场、多因素耦合作用下的强震灾害链级联演化机理。

(2)突破强震地质灾害风险预测瓶颈:发展动力学机理、人工智能与高性能计算深度融合的灾害链风险模拟预测新范式。基于空天地协同监测多源数据,通过深度学习和计算机视觉驱动的智能算法,实现强震灾害本底数据库质量和精细化建模能力的跃升;依托高性能计算平台,通过AI算法优化参数配置,不断提升跨尺度、多

图3　强震地质灾害机理与风险预测研究展望

Fig.3　Outlook on the Mechanisms and Risk Prediction of Strong Earthquake-triggered Geohazards

过程、多灾种耦合的数值模拟能力,实现复杂地质环境条件下灾害链全过程高精度数值模拟;研发机理与数据联合驱动的强震地质灾害预测大模型,构建基于数字孪生的灾害链情景推演与智能风险预测系统,赋能复合灾害链风险管控。

(3)**探究强震地质灾害长期环境效应**:构造活动频繁的地区,强震地质灾害已被证实是陆地碳库扰动的重要驱动力,尤其是在生态脆弱带与碳汇核心区高度重叠的背景下,其影响不容忽视。当前研究虽已揭示地震滑坡促进有机碳埋藏的潜在碳汇功能,但对震生沉积物中有机碳的迁移机制、储存通量及其长期演化路径仍缺乏系统认知。未来研究应加强多源数据集成与高时空分辨率监测技术,利用遥感、无人机、同位素分析等手段获取震区碳库变化的连续观测数据,为模型校验和过程机制识别提供支撑;发展耦合地貌演化与碳循环的多尺度模型,融合滑坡物质运移、沉积物输运与有机碳跨圈层迁移过程,模拟强震扰动下碳的短期剧变与长期演化趋势。

(4)**健全强震地质灾害风险防控体系**:强震地质灾害风险防控是国家自然灾害防治体系建设的重要组成部分。其有效实施不仅依赖管理政策,更必须以坚实的科学研究为核心支撑,对我国高地震烈度区的防灾减灾、国家重大工程安全和经济社会高质量发展至关重要。全面提升应对强震地质灾害风险的能力,需要多学

科交叉和多部门联动,通过对潜在活动断裂带的破裂模拟和预设地震诱发地质灾害的预测,支撑震前城镇、基础设施和重大工程规划,将防灾减灾端口前移,做到以“防”为主;震后地质灾害防控则以支撑“应急响应”和“重建恢复”为主,重点在于建立科学的灾害应急管理体系(涉及应急调查、灾损快速评估、应急处置与救援、物资调配与管理等)和风险管控体系(震后灾害监测预警、韧性防控、动态风险评价与管理等),为世界强震地质灾害研究与防控提供中国案例。

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Challenges and Responses in the Mechanisms and Prediction of Strong-earthquake-triggered Geological Hazards

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Abstract Strong earthquakes are one of the major triggers of geological hazards in mountains,posing severe threats to human lives,property security,high-quality socioeconomic development,and the safety of national infrastructure projects. With the rapid expansion of urban construction,the implementation of major national projects,and the intensifying impacts of climate change,the risks of geological hazards induced by earthquakes and extreme climate events have markedly increased. However,systematic studies on the chain evolution mechanisms of earthquake-triggered hazards and their risk prevention and control strategies remain insufficient. This paper reviews recent advances in three key aspects:The initiation mechanisms and susceptibility prediction of coseismic landslides,the post-seismic hazard chain evolution mechanisms and forecasting approaches,and the long-term effects of earthquake-triggered geological hazards. We identify two fundamental

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scientific and technical challenges:(1) understanding the cross-scale spatiotemporal evolution laws and dynamic mechanisms of strong-earthquake hazard chains,and (2) developing data- and mechanism-driven predictive frameworks for hazard risks. To address these challenges,we suggest adopting an Earth system science perspective to investigate how tectonic forces and climate change jointly affect the shallow lithosphere,and to explore the disaster-forming environments shaped by tectonic-climate-geomorphic interactions. This requires the establishment of a long-term database of strong-earthquake-induced hazards to reveal their spatiotemporal evolution;the elucidation of slope seismic response processes and cascade evolution mechanisms under cross-scale,multiphase,multi-field,and multi-factor coupling;and the development of new paradigms for hazard chain risk simulation and prediction through the deep integration of dynamic process models, artificial intelligence,and high-performance computing. Furthermore,by promoting interdisciplinary collaboration and cross-sectoral coordination,it is essential to strengthen emergency response and risk prevention systems for strong-earthquake-triggered hazards,thereby supporting the construction of an efficient and scientific national disaster prevention and control framework and contributing Chinese case studies to global research and mitigation of strong-earthquake geological hazards.

Keywords　strong earthquake-triggered geological hazards;hazard chain mechanisms;monitoring and early warning; susceptibility prediction;natural hazard prevention and control system

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