一种新型城市地震灾害模拟方法: 城市抗震弹塑性分析方法

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摘要 城市地震灾害模拟可服务震前防灾规划和震后快速救援, 对降低城市震害风险具有重要价值. 本研究提出了一种新型城市地震灾害模拟方法——城市抗震弹塑性分析方法, 给出了海量建筑建模、高性能计算、“场地-城市效应”、高真实感可视化与次生灾害预测等系列关键科学问题的解决方法, 并应用于震后灾损近实时评估(九寨沟)、震前防震减灾规划(唐山)、城市中心区高层建筑群多尺度震害模拟(北京CBD)、城市建筑震害及次生灾害全过程模拟(旧金山湾区)等, 可为城市防震减灾提供重要决策参考.

关键词 城市抗震弹塑性分析, 建筑群多尺度模型, 高性能计算, 次生灾害, 工程应用

地震会造成严重的经济损失与人员伤亡^[1]. 随着城镇化发展, 人口与财富高度聚集, 加重了城市面临的地震威胁. 因此, 针对震害的主要承灾体——建筑, 开展高效、合理的建筑震害模拟, 有助于揭示灾变机理, 服务震前防灾规划和震后应急救援, 对降低城市震害风险具有重要价值.

目前, 广泛采用的城市建筑震害模拟方法包括易损性矩阵方法^[2]和能力-需求方法^[3]等. 易损性矩阵方法是一种数据驱动的方法, 它高度依赖历史震害数据, 对震害数据不足的地区(如我国大陆中东部城市)难以应用; 能力-需求分析方法基于单自由度静力推覆分析, 难以考虑结构高阶振型、软弱层以及地震动时域特性的影响, 分析结果准确性不足.

因此, 本研究提出采用“城市抗震弹塑性分析方

法”实现高效、准确的城市建筑震害模拟^[4]. 本方法基于结构动力学理论, 采用完整的地震动时程记录, 对城市中每栋建筑逐一开展动力弹塑性时程分析, 可充分反映地震动时域和频域特征及建筑抗震特性, 比传统方法具有明显优势. 为实现该方法, 需解决海量建筑建模、高性能计算、“场地-城市效应”、高真实感可视化、次生灾害预测等一系列关键科学问题. 因此, 本研究分别提出了: (1) 基于物理驱动模型的建筑群多尺度模型; (2) 基于CPU/GPU异构并行的高性能计算方法; (3) 考虑“场地-城市效应”的区域建筑震害分析方法; (4) 基于3D城市模型和无人机倾斜摄影的震害高真实感展示方法; (5) 基于精细化模拟和新一代性能化设计的震损预测和次生灾害模拟方法. 基于上述方法, 开展了震损应急评估、城市震害预测、地震情境和次生灾

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害模拟等, 为相关研究与决策提供了重要参考.

1 城市抗震弹塑性分析方法

1.1 技术框架

本研究提出的城市抗震弹塑性分析方法技术框架如图1所示^[5].

1.2 基于物理驱动模型的建筑群多尺度模型

本研究将城市中的建筑划分为常规多层建筑、常规高层建筑和特殊建筑, 并分别提出力学/物理驱动的震害预测模型. (1) 常规多层建筑在地震下以剪切变形为主, 可采用非线性多自由度(multiple-degree-of-freedom, MDOF)剪切层模型^[6](图2(a)), 该模型采用剪切梁连接简化为质点的每个楼层, 剪切梁恢复力关系采用

HAZUS报告^[3]推荐的三线性骨架线(图2(c))以及单参数滞回模型^[7](图2(d)); (2) 高层建筑以弯剪耦合变形模式为主, 可采用MDOF弯剪层模型^[8](图2(b)), 该模型每层用弯曲梁和剪切梁并联模拟; (3) 城市内大跨结构、超高层等特殊建筑动力特性复杂, 可采用基于纤维梁和分层壳模型的精有限元模型分析^[9].

由于可获取城市建筑信息有限, 本研究提出了MDOF模型的关键参数确定方法. (1) 基于易获取的宏观GIS数据, 包括结构高度、类型、建设年代、面积、层数、功能等, 采用经验公式确定结构振动特性; (2) 根据设计规范确定结构设计承载力; (3) 根据相关统计关系确定建筑实际抗震性能. 如能获取详细设计信息, 则可直接确定模型参数, 提升计算精度. 本研究也提出了基于力和位移的损伤判别准则^[6,8], 共考虑5种破坏状态(基本完好、轻微破坏、中等破坏、严重破坏、毁

图1 城市建筑抗震弹塑性分析技术框架

Figure 1 Framework of city-scale nonlinear time-history analysis of buildings

图2 建筑计算模型. (a) MDOF剪切层模型; (b) MDOF弯剪层模型; (c) 三线性骨架线; (d) 单参数滞回模型

Figure 2 Building analysis model. (a) MDOF shear model; (b) MDOF flexural-shear model; (c) tri-linear backbone curve; (d) single parameter pinching model

坏). 通过与实际震害结果的对比, 上述方法的准确性与可靠性已经得到了验证^[5].

1.3 基于CPU/GPU异构并行的高性能计算方法

城市抗震弹塑性分析的计算量巨大, 因此, 本研究提出CPU/GPU异构并行计算方法^[4]. 为充分利用GPU计算能力, 本方法满足以下原则: (1) 采用GPU进行时程计算, 避免参与过多逻辑计算; (2) 采用CPU完成数据读取等高逻辑计算需求; (3) 减少内存和显存的数据交互, 降低数据传输延迟. 方法流程如图3(a)显示CPU分配计算任务; GPU执行建筑时程分析; CPU将GPU计算结果输出用于后处理. 案例分析表明(图3(b)), 在相近成本下, 本方法单精度计算加速比达到39倍, 满足城市区域建筑震害模拟“低成本-高效率”的实际需求. 另外, 这里采用的64位架构CPU默认双精度模式, 采用单精

度计算需耗时转换, 故CPU单精度计算时间略高.

1.4 考虑“场地-城市效应”的区域建筑震害分析方法

在建筑密集的城市区域, 大量高层建筑在空间上紧密分布, 显著改变了场地特征与建筑的地震动输入. 这种宏观上由城市与场地之间相互作用带来的影响被称作“场地-城市效应”(简称SCI效应). 本研究结合开源谱元分析程序SPEED及1.2节的非线性MDOF建筑模型, 提出了考虑SCI效应的区域建筑震害耦合数值模拟方法^[10](图4).

该方法包含两个主要部分: (1) 采用SPEED计算地震波在土体中的传播; (2) 采用非线性MDOF模型分析建筑响应. 为耦合这两部分, 在每个计算时间步, 将建筑所在位置地面运动加速度作为建筑的基底输入用于建筑分析, 并提取建筑的底部反力用于场地地震波传

图3 CPU/GPU异构并行计算方法与效率. (a) 计算流程; (b) 与仅CPU计算效率对比

Figure 3 CPU/GPU heterogeneous parallel computing method and its efficiency. (a) Computing procedure; (b) efficiency comparison with CPU computing

图4 SCI效应的耦合数值模拟方法

Figure 4 Numerical coupling scheme for SCI effects

播分析. 通过合理建模, 该方法可以考虑建筑深基础与土体非线性, 进而更加准确地反映SCI效应^[11].

1.5 基于3D城市模型和倾斜摄影的震害高真实感展示方法

高真实感的震害展示有助于政府官员、消防队员等非结构工程专业用户的理解与决策. 随着信息技术的发展, 大量城市开始拥有高真实感3D模型^[12]. 因此, 本研究提出了基于3D城市模型的震害高真实感展示方法^[13](图5(a)), 主要流程包括建筑对象识别、楼层平面生成与位移插值. 由于3D城市模型缺乏必要纹理, 本研究提出了基于无人机倾斜摄影的震害场景增强现实可视化^[14](图5(b)), 主要流程包括轻量级建模、建筑单

体识别、动态响应可视化.

1.6 基于精细化模拟和新一代性能化设计的震损预测和次生灾害模拟方法

合理的地震经济损失预测可以有针对性地辅助制定防震减灾规划和地震保险规划等. 本研究基于城市抗震弹塑性分析结果, 结合FEMA P-58新一代性能化抗震设计方法, 提出了建筑地震经济损失预测方法^[15](图6). 该方法根据结构动力响应和FEMA P-58的易损性数据库获取每层不同构件的精细化震损情况(包括经济损失、修复时间等)^[15], 可同时考虑楼层位移、加速度、残余变形的影响.

精细化震损模拟结果也可以进一步用于次生灾害

图5 震害高真实感展示方法. (a) 基于3D城市模型的展示方法; (b) 基于倾斜摄影的展示方法

Figure 5 High-fidelity visualization methods using. (a) 3D urban polygon models; (b) oblique aerial photography

图6 震损预测和次生灾害模拟方法

Figure 6 Earthquake loss prediction and secondary disaster simulation method

的预测。针对建筑外围护结构受地震脱落致人伤亡并阻碍疏散的问题,本研究提出了坠物影响范围预测方法^[16](图6),基于结构动力响应判断失效构件,结合坠物分布计算模型确定坠物范围,进而为避难场所规划和疏散道路设计提供参考;针对次生火灾问题,本研究提出了城市次生火灾情境模拟方法^[17](图6),基于结构动力响应判断起火点,结合蔓延模型计算火灾蔓延情况,分析结果可为城市消防规划和灾后应急预案编制提供参考。

2 城市抗震弹塑性分析方法的实际应用

2.1 震后灾损近实时评估

震后灾损近实时评估对震后应急救援具有重要价值,因此本研究提出了一套基于城市抗震弹塑性分析的近实时震后灾损评价方法^[18]。该方法通过地震台站获取发震地区实测地面运动记录,对发震地区建立典型区域建筑数据库并开展城市抗震弹塑性分析,进而评估地震破坏力,包括每栋建筑的损伤状态、各种损伤状态建筑的比例等。该方法能考虑结构抗力不确定性、地震动时域与频域特征以及建筑动力特征;可在震后快速评估地震对目标区域建筑群的破坏力,为抗震救灾决策制定提供了有力工具。该方法已在32次境内地震、42次境外地震中得到成功应用。例如,2017年九寨沟7.0级地震破坏力分析为典型的应用案例,在震后5 h内给出震害预测结果,且与实际震害较为一致,精度显著优于传统方法,限于本文篇幅,详细分析可参见文献^[18]。

2.2 震前防震减灾规划

预测城市未来遭受地震灾害时的损失情况,对城市防震减灾决策具有重要价值。以唐山市为例,唐山地震40周年时,作者通过和唐山市以及清华同衡规划院合作,采用城市抗震弹塑性分析方法,分析了当今唐山市区230683栋建筑物再度遭遇1976年唐山地震可能产生的破坏^[19]。分析结果表明,建筑平均倒塌率(倒塌建筑楼层面积与所有建筑楼层面积的比值)为33.84%,且大部分倒塌的建筑为未设防老旧建筑,相比1976年唐山市建筑的抗倒塌能力(倒塌率超80%)有了显著提升。但是,有超过 $1.0 \times 10^8 \text{ m}^2$ 的建筑损伤非常严重,基本不具备修复价值。因此,提高城市的抗震“韧性”极为重要。该成果直接服务于唐山市防震减灾规划,为提高城市

抗震能力提供了重要参考资料。

2.3 城市中心区高层建筑群多尺度震害模拟

1679年,在北京东郊三河-平谷地区发生过一次震级估计为8级的强烈地震,造成了非常严重的破坏。因此,针对该地震情境开展北京中心城区震害预测对北京市防震减灾工作具有重要价值。本研究建立了北京CBD核心区内170余栋高层和超高层建筑的多尺度模型,并通过与中国地震局地球物理研究所合作,使用三河-平谷地震场景下地表宽频带地震动时程场模拟结果,开展了高层建筑群多尺度震害模拟研究^[20]。结果表明,北京CBD建筑基本为轻微和中等破坏。图7给出了损伤可视化结果,可以看出本方法在复杂建筑群震害模拟方面有着明显的优势。

2.4 城市建筑震害及次生灾害全过程模拟

城市震害全过程模拟包括断层破裂、地震波传播、建筑响应、经济损失和修复时间预测,以及次生灾害模拟,对防震减灾工作意义重大,但是涉及多学科交叉,难度较大。作者通过与美国国家科学基金重大项目“多灾害模拟平台”(SimCenter)合作,采用城市抗震弹塑性分析方法开展了旧金山湾区震害情境模拟,并将模拟程序开源^[21]。本案例共统计了旧金山湾区1843351栋建筑的基本信息,并采用美国劳伦斯-伯克利国家实验室模拟的Hayward断层M7.0级地震在旧金山及周边引起的地面运动^[22],分析了旧金山湾区180余万栋建筑的损失比和修复时间比中位值分布(图8(a))。进一步分析的地震次生火灾场景结果表明,由于起火区域建筑的间距较大,地震次生火灾并不太严重。另外,通过在次生火灾场景中添加烟气效果,既可以提高场景真实感,又能明显地标示出燃烧建筑(图8(b))。

3 结论和展望

科学、准确、直观地模拟城市地震情境并预测地震损失对城市防震减灾工作具有重要价值。随着强震台网的建设、数据传输网络的完善以及计算机分析速度的提高,城市抗震弹塑性分析方法在提升震害预测和评估的准确性、高效性和真实感方面具有巨大的优势和前景。本研究简要介绍了城市抗震弹塑性分析方法的技术框架和典型应用,并展示了该方法的可行性和优势。由于该方法属新生事物,仍需要在建筑模型、震损评估方法、次生灾害预测方法等方面开展深入研究,并引入

图 7 三河-平谷地震下北京CBD建筑损伤响应可视化(变形放大50倍). (a) $t = 10$ s; (b) $t = 20$ s

Figure 7 Damage states of the buildings in Beijing CBD under Sanhe-Pinggu earthquake (displacement scale ratio: 50). (a) $t = 10$ s; (b) $t = 20$ s

图 8 旧金山湾区震害情境模拟. (a) 建筑经济损失比与修复时间比; (b) 次生火灾场景可视化效果

Figure 8 Seismic scenario simulation of the San Francisco Bay Area. (a) Loss ratio and repair time ratio; (b) post-earthquake fire visualization

建筑以外的其他基础设施模型(如桥梁、生命线等), 完善地震破坏力分析方法. 在未来, 还可以基于此方法,

进一步开展多灾害下的城市建筑群损伤预测研究, 为提升城市综合防灾能力提供更加全面的参考.

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Summary for “一种新型城市地震灾害模拟方法: 城市抗震弹塑性分析方法”

A new urban earthquake disaster simulation method: City-scale nonlinear time-history analysis

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Earthquakes can cause severe damage and huge economic loss to modern cities. Accurate and efficient seismic damage simulations of buildings have therefore become an indispensable part of earthquake hazard mitigation effort worldwide. Rational simulation results can help to illustrate potential seismic damage and can further provide an essential reference for city planning and post-earthquake rescue work. Motivated by the above, a new urban earthquake disaster simulation method, i.e., city-scale nonlinear time-history analysis (THA), is performed in this research work. The key scientific outcomes achieved are addressed below:

(1) Physics-based multi-scale modeling method for urban buildings. Urban buildings can be classified into three types: Ordinary multi-story buildings, ordinary tall buildings, and special buildings. Corresponding analysis methods are proposed: Multi-story buildings can be simulated using nonlinear multiple-degree-of-freedom (MDOF) shear model; tall buildings can be simulated using nonlinear MDOF flexural-shear model; special buildings, such as large-span spatial structures and super tall buildings, can be established using the refined finite element models based on the fiber beam-column and multi-layered shell elements.

(2) CPU/GPU collaborative parallel computing method. Seismic damage simulations often result in excessive computational workload. Therefore, a CPU/GPU collaborative parallel computing method is proposed: CPU will assign tasks to GPU; GPU will perform the nonlinear THA of each building; CPU will then copy result data from GPU for post-processing. Case study results show that, the proposed method can achieve a speed up of 39, compared with traditional CPU computing method with similar hardware cost.

(3) Numerical coupling scheme for site-city interaction simulations. Interactions among densely distributed buildings in a city and the site, i.e., the site-city interaction (SCI) effects, can significantly influence the seismic behavior of buildings. Therefore, a numerical coupling scheme is proposed: Nonlinear MDOF models are used to represent different buildings above the ground, while an open-source spectral element program, SPEED, is used to simulate wave propagation in soil layers. The proposed numerical scheme is validated and proved useful for investigating the SCI effects.

(4) High-fidelity visualization method using 3D urban polygon models and oblique aerial photography. Seismic simulation of urban buildings often produces a large number of computational results, which would be difficult to comprehend without appropriate visualizations. Thus, a high-fidelity visualization method using 3D urban polygon model is proposed, which covers three major components: Building identification, floor plan generation and displacement interpolation. In addition, to achieve a more realistic seismic damage scenario, a photo-realistic visualization method based on oblique aerial photography is proposed, including lightweight modeling, building segmentation, and dynamic visualization. Using these methods, high-fidelity visualization of seismic simulation results can be achieved.

(5) Seismic loss prediction and secondary disaster simulation methods for urban buildings. Based on FEMA P-58 (next generation seismic performance assessment method of buildings) and the city-scale nonlinear THA, a practical approach for refined regional seismic loss prediction is proposed. In addition, the secondary disaster simulation for falling debris and fire following earthquake are proposed. Such a simulation will provide a useful reference for seismic loss assessment, site selection of emergency shelters, evacuation plan design, urban fire safety planning, and post-disaster emergency planning.

The proposed disaster simulation method has been adopted by the SimCenter supported by the National Science Foundation of the United States to perform a seismic damage simulation and loss prediction for 1.8 million buildings in the San Francisco Bay Area. The proposed method has also been successfully applied to the seismic damage prediction of other cities, such as Beijing and Tangshan. Combined with the real-time recorded ground motions, the proposed method has been successfully used for the prompt assessment of seismic damage in 32 domestic and 42 international earthquakes. The assessment results (e.g., Jiuzhaigou Earthquake) agreed very well with the actual building damage.

In summary, the city-scale nonlinear THA takes accurate consideration of the characteristics of ground motions and those of buildings, and the analysis outcomes will provide an important reference for city planning, post-earthquake rescue work, seismic damage assessment, and earthquake scenario simulation.

city-scale nonlinear time-history analysis, multi-scale models for urban buildings, high performance computing, secondary disasters, engineering applications

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