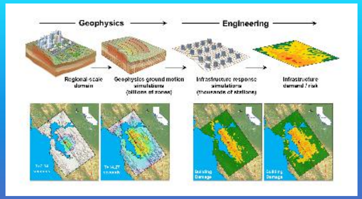

PEER International Pacific Rim Forum
June 16-17, 2021

Physics-driven city-scale disaster simulation methods and applications

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06/17/2021

Tsinghua University

PEER

Outlines

1. Research Background
2. Multi-hazard simulation framework based on CIM
3. Physics-driven regional earthquake simulation
4. Physics-driven fire, wind/COVID-19 simulation of communities
5. Conclusions

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1. Research Background
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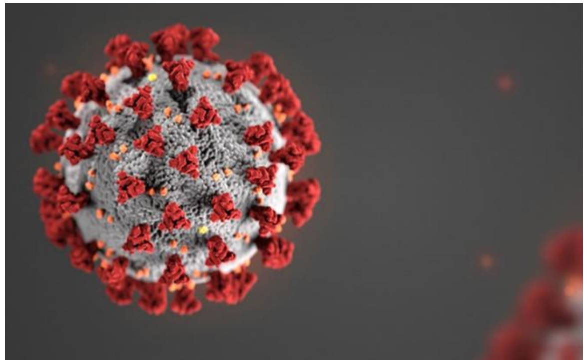
1 Research Background

- Cities are facing the threats of many disasters

Christchurch **earthquake**
$40 billion loss
5 years recovery

Beijing Television Center **fire**
$23.99 million loss

Typhoon Soudelor
59 killed,
$4.09 billion loss



COVID-19
3.76 million killed,
174 million confirmed cases

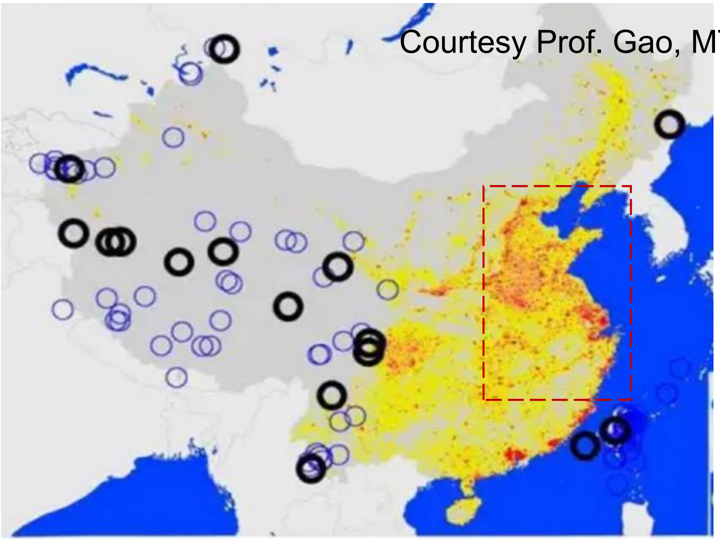
Quantifying the performance of the community under multiple potential hazards is important

1 Research Background

- City-scale disaster simulation models
  - Empirical models are widely-used
  - e.g., Earthquake: damage probability matrices

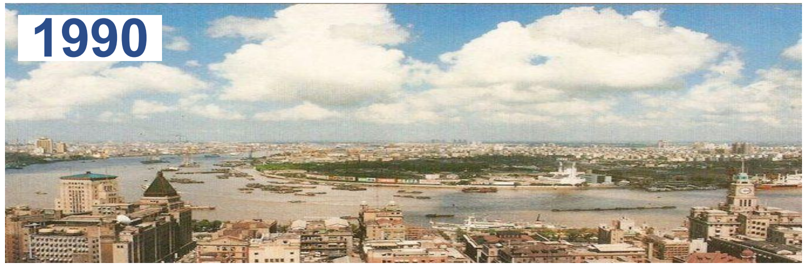
Challenges

Limited historical data



No strong earthquake in dense population area of China mainland for 45 Years

Not adaptive to new structures

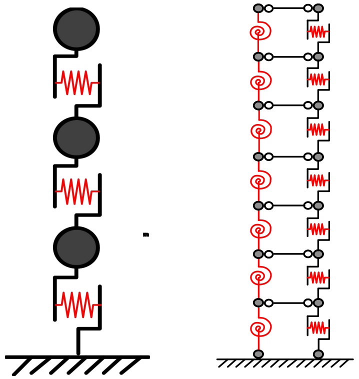


Many new structures are emerging

1 Research Background

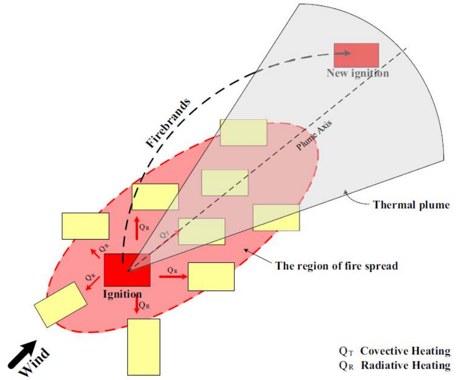
- Challenges of empirical models
  - Limited historical data
  - Not adaptive to new structures
- Solutions: **Physics-driven model**
  - **Reliable, Efficient, Adaptive**

Earthquake



Nonlinear time-history analysis

Fire



Thermal plume and radiation-based fire spread simulation

Wind / COVID-19

Continuity: $$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

X – Momentum: $$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial p}{\partial x}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}\right]$$

Y – Momentum: $$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=-\frac{\partial p}{\partial y}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}\right]$$

Z – Momentum $$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}\right]$$

Energy:
$$\frac{\partial(E_T)}{\partial t}+\frac{\partial(uE_T)}{\partial x}+\frac{\partial(vE_T)}{\partial y}+\frac{\partial(wE_T)}{\partial z}=-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}-\frac{1}{Re_rPr_r}\left[\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right]$$
$$+\frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\tau_{xx}+v\tau_{xy}+w\tau_{xz})+\frac{\partial}{\partial y}(u\tau_{xy}+v\tau_{yy}+w\tau_{yz})+\frac{\partial}{\partial z}(u\tau_{xz}+v\tau_{yz}+w\tau_{zz})\right]$$

Large eddy simulation

Outlines

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2.1 Multi-hazard simulation framework based on CIM

Problem

Physics-driven simulations of different hazards require different types of data

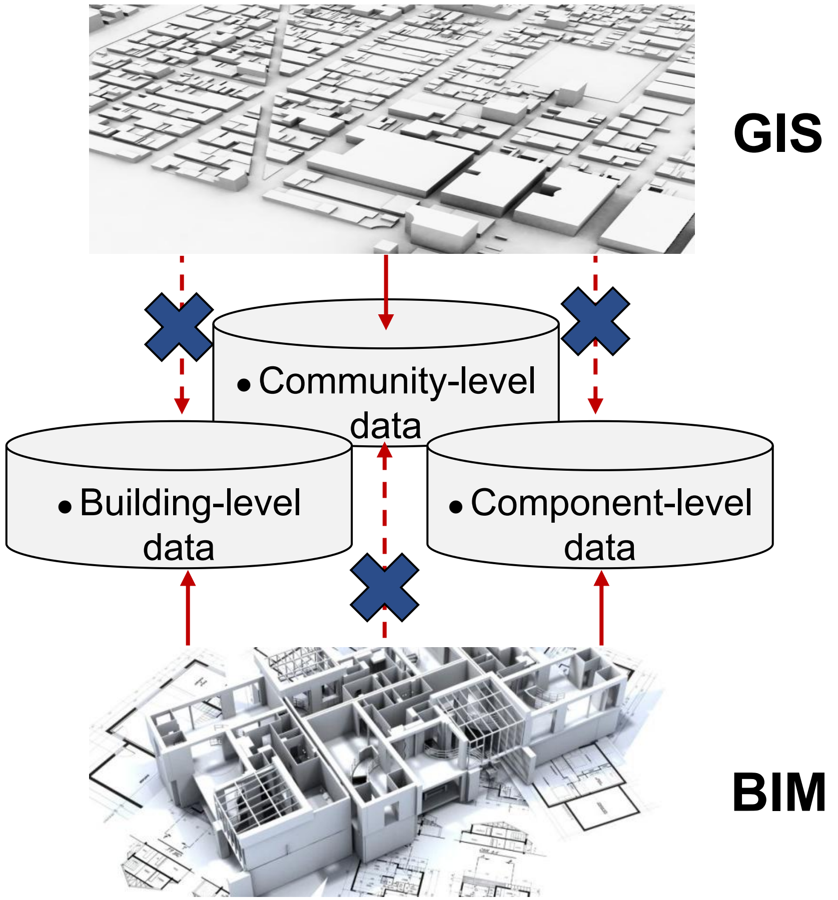
Earthquake simulation
- Structural information
- Non-structural information
- Ground motion

Fire simulation
- Building information
- Initial ignited building
- Some indoor equipment like sprinkler systems

Wind / COVID-19 simulation
- Building configuration
- Weather conditions

State of the art

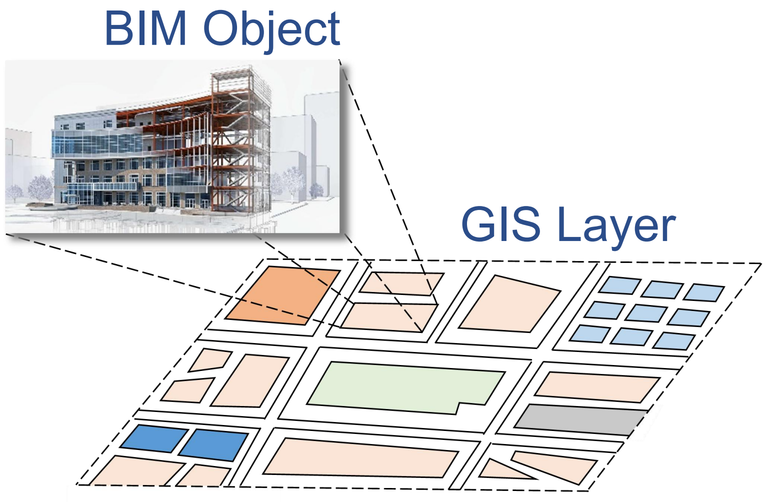
Commonly-used data format cannot meet the data requirement

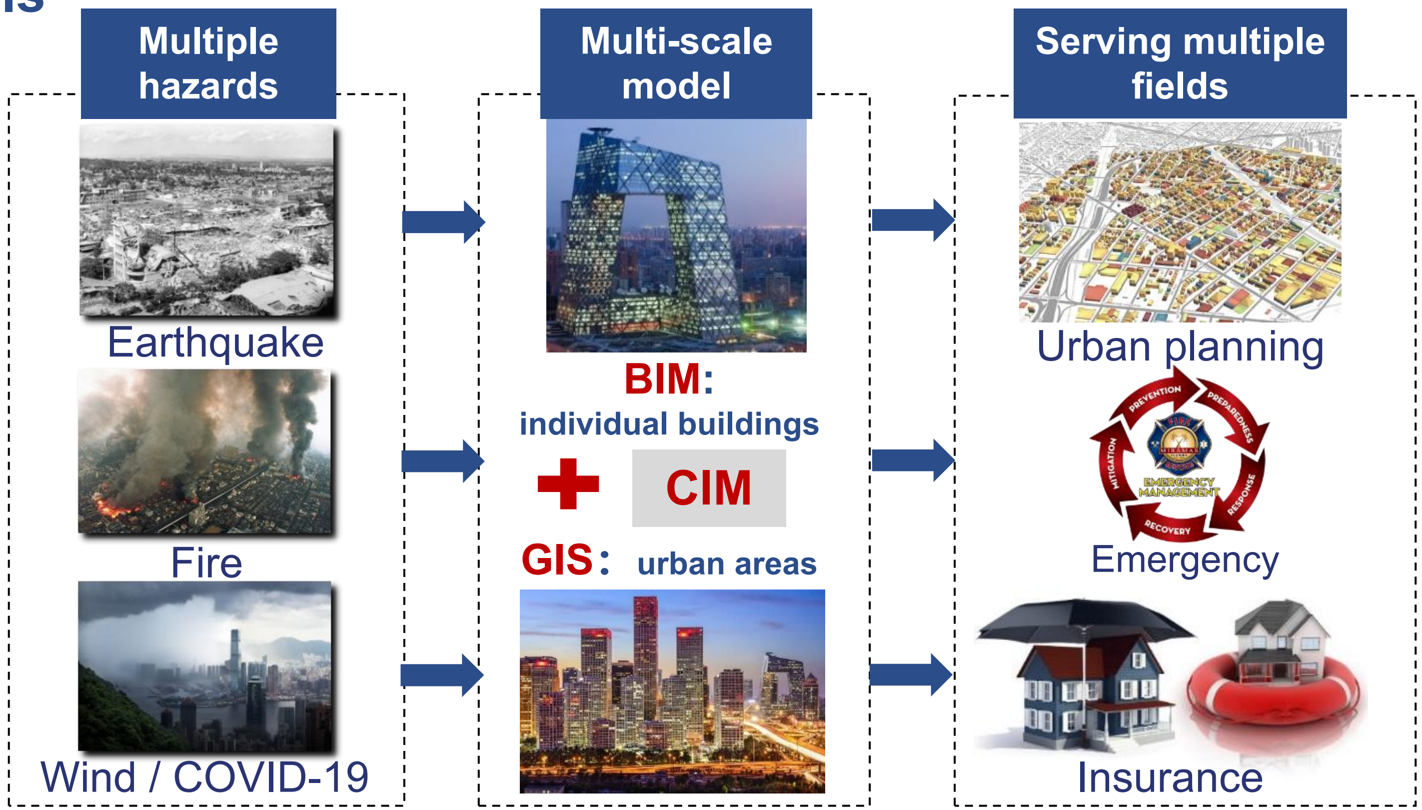


2.1 Multi-hazard simulation framework based on CIM

City information model
CIM = GIS + BIM

- **Physics-driven hazard simulation models**
- **Multiple hazards: earthquake, fire, wind / COVID-19**
- **Individual buildings + regional scales**

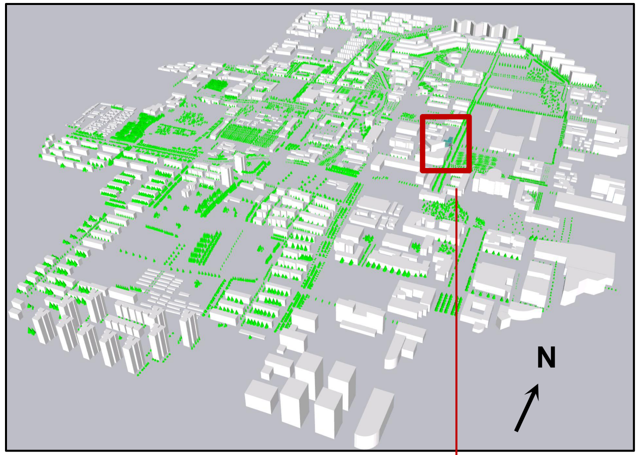




CIM-powered multi-hazard simulation framework covering both individual buildings and urban areas, Sustainability, 2020.

2.1 Multi-hazard simulation framework based on CIM

▪ Automatic data transformation

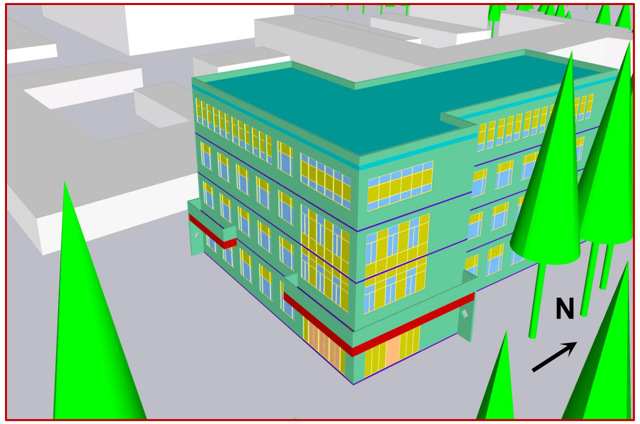


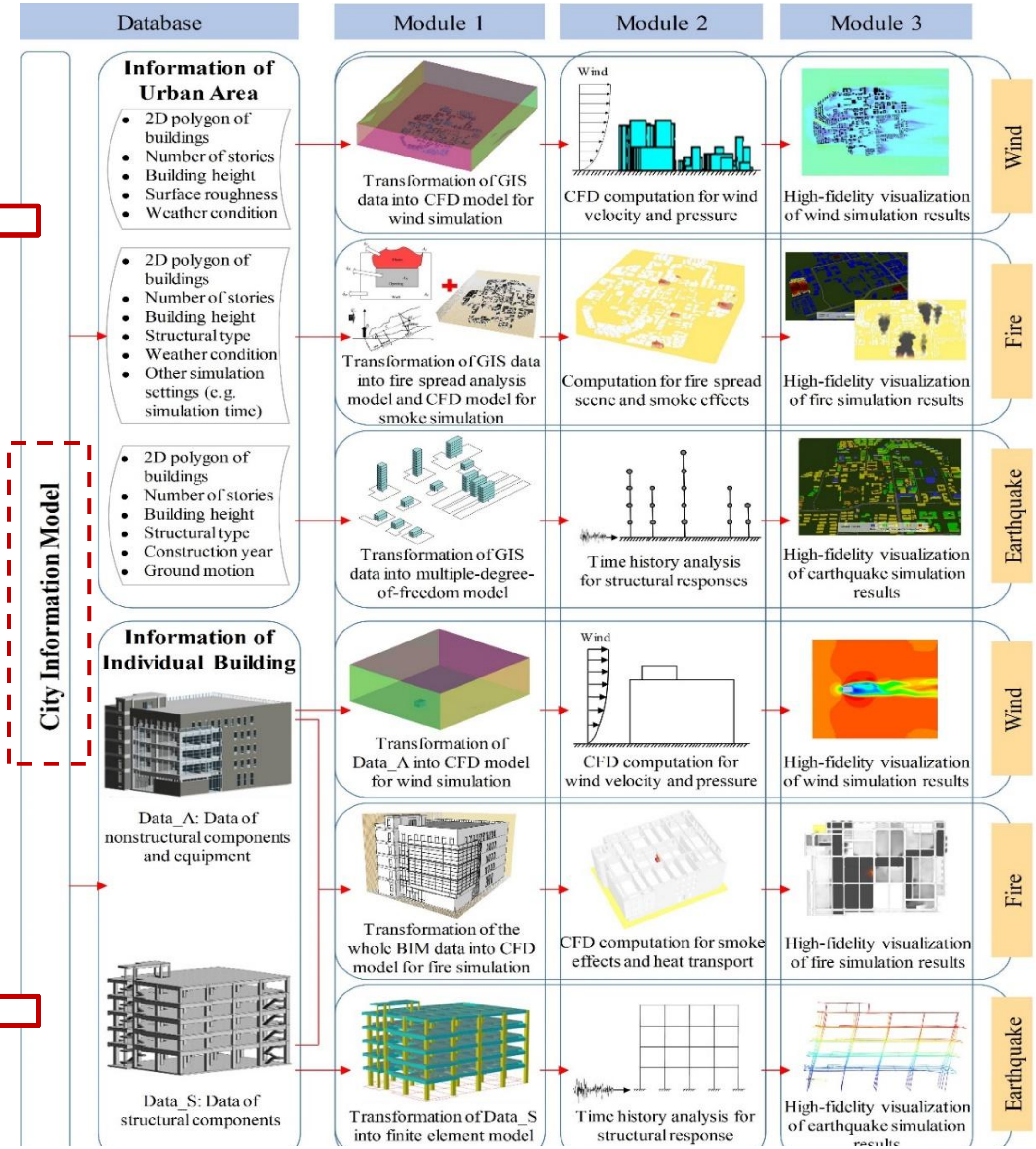
For communities

Unified data format

For individual buildings

CIM = GIS+BIM

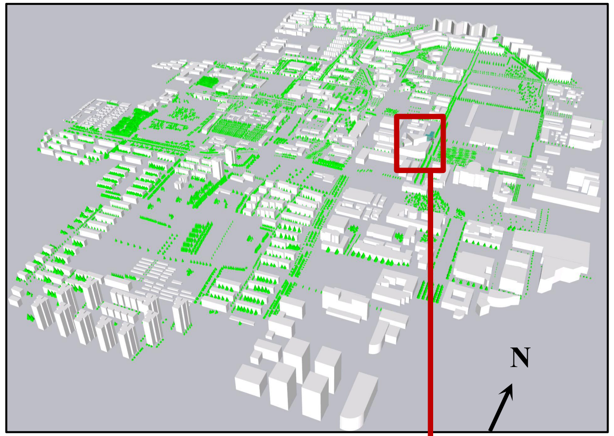




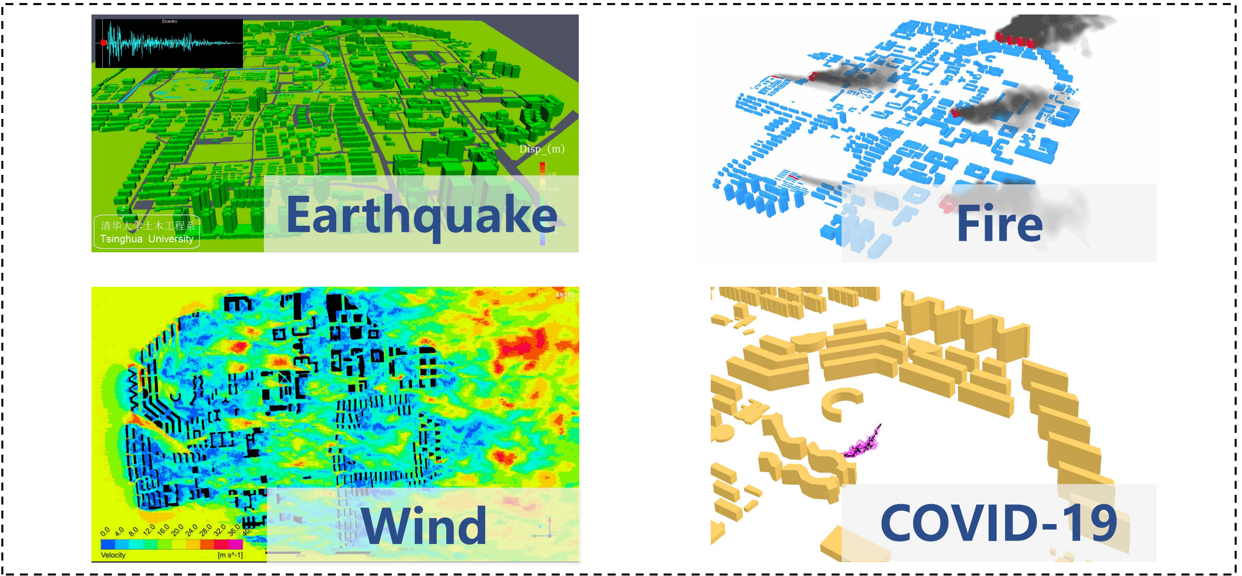
CIM-powered multi-hazard simulation framework covering both individual buildings and urban areas, Sustainability, 2020.

2.2 Case study: Tsinghua campus, multiple hazards

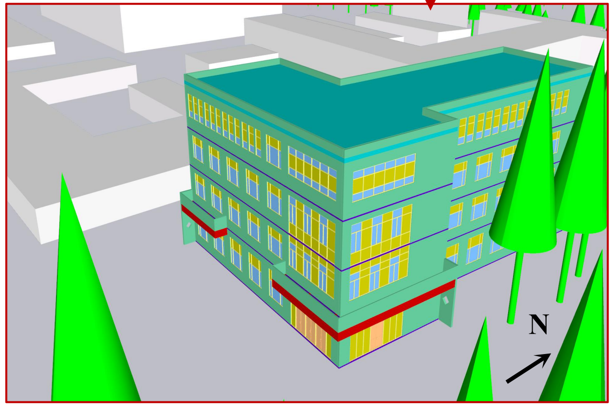
Entire campus



Regional Scale

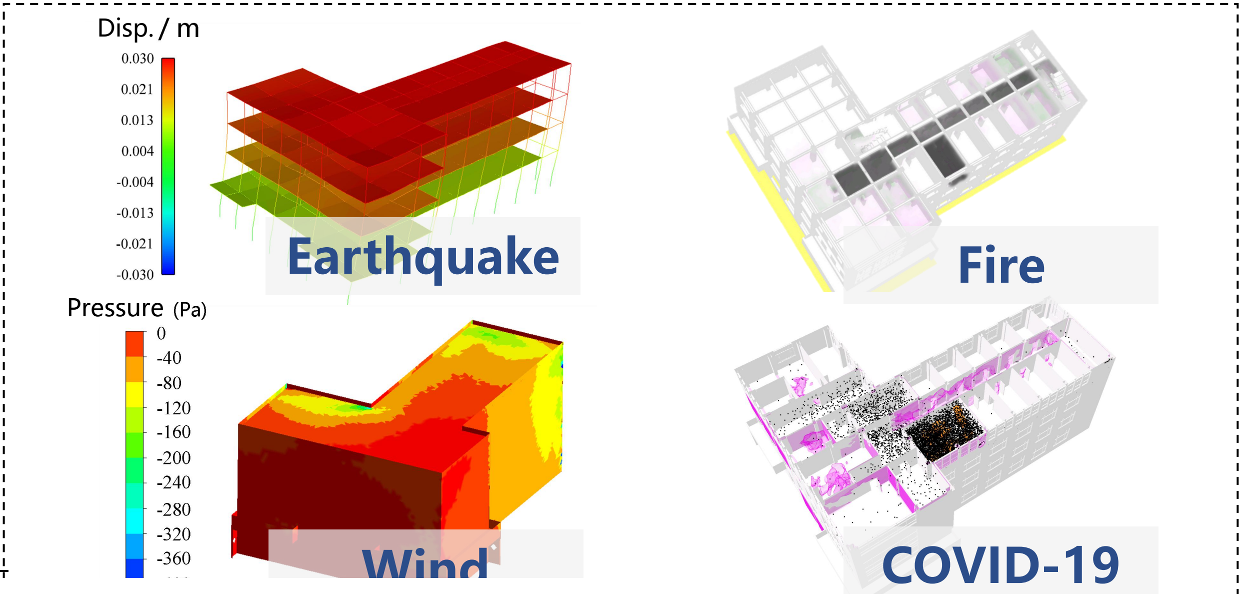


CIM = GIS+BIM



4-story RC building

Building Scale



CIM-powered multi-hazard simulation framework covering both individual buildings and urban areas, Sustainability, 2020.

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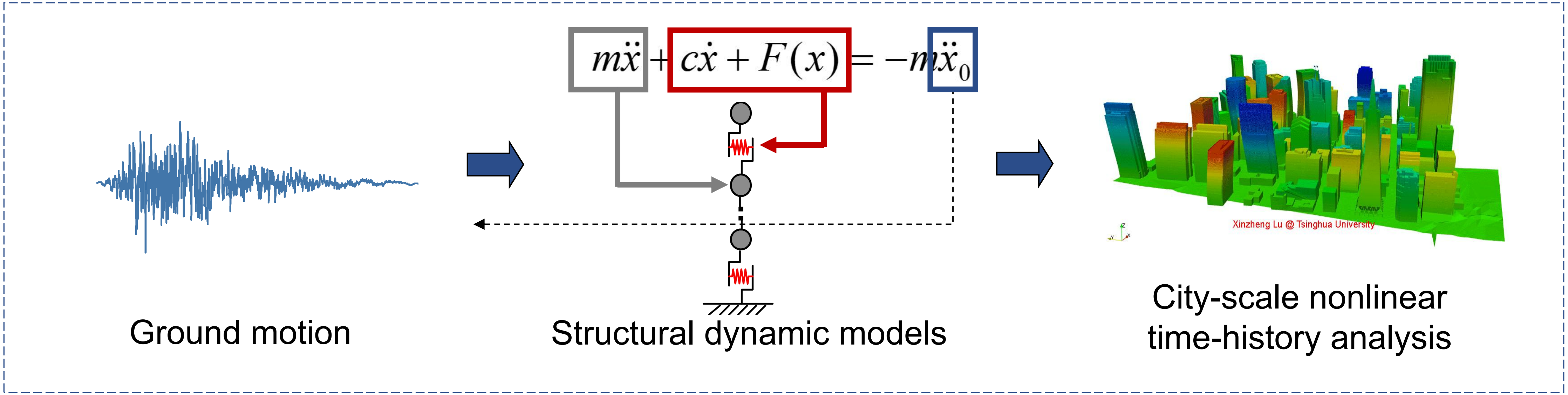
3 Physics-driven regional earthquake simulation

- **Physics-driven**: structural dynamic models + city-scale nonlinear time-history analysis



Advantages

✓ **Strictly follow fundamental of structural dynamics**

✓ **Accurately represent features of individual buildings**

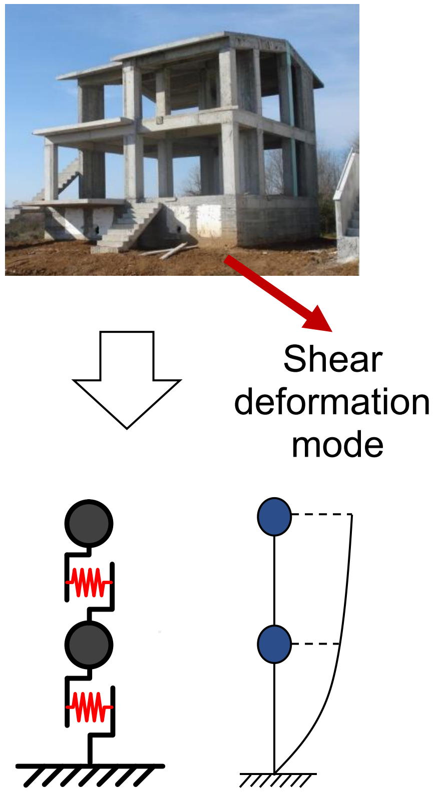
✓ **Accurately represent characteristics of ground motions**

Lu XZ, Guan H, Earthquake Disaster Simulation of Civil Infrastructures: From Tall Buildings to Urban Areas (2nd Ed.), Singapore: Springer, 2021.

3 Physics-driven regional earthquake simulation

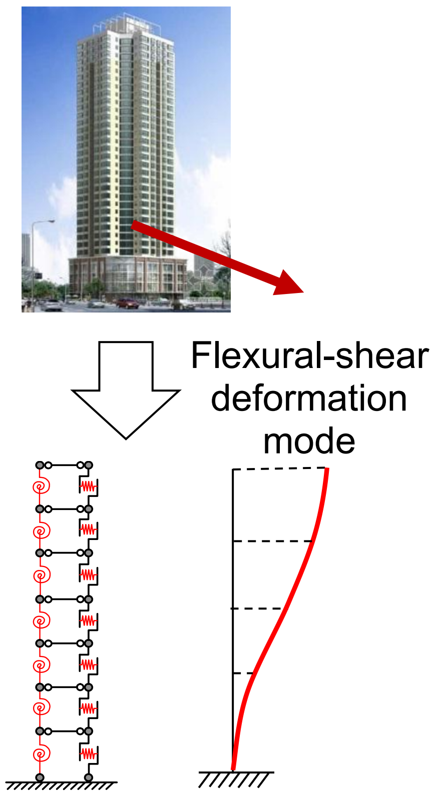
- Multi-scale structural dynamic models

Multi-story buildings



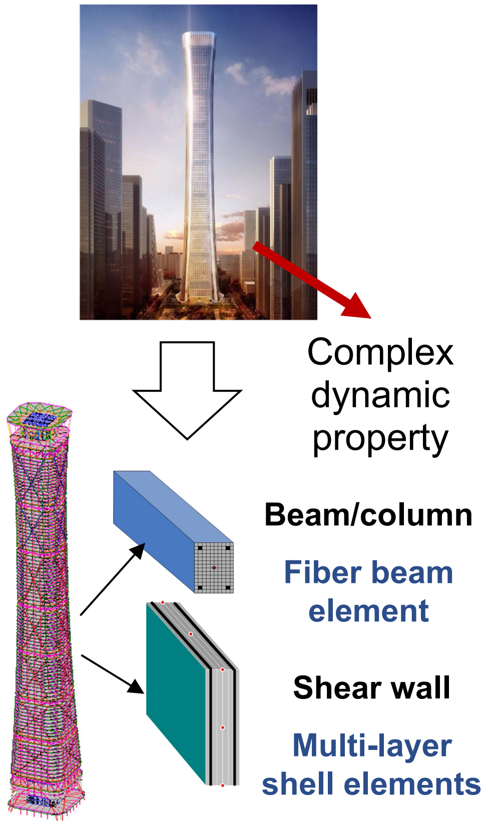
MDOF shear model

Tall buildings



MDOF flexural shear model

Special buildings



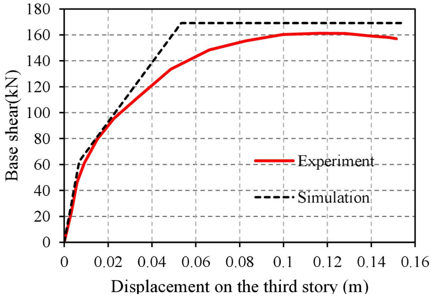
Refined FE model

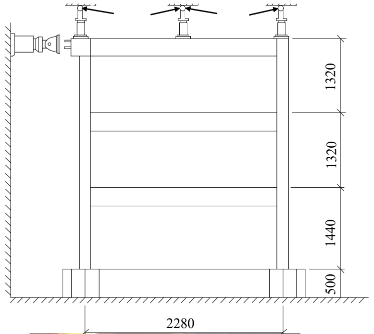
Moderate-fidelity models

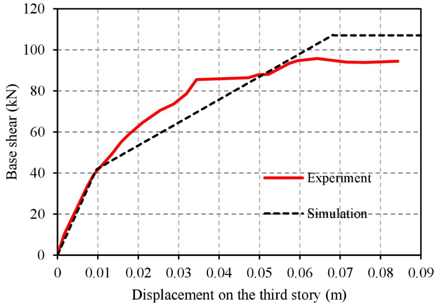
High-fidelity models

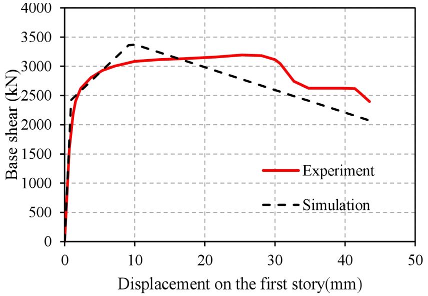
3.1 Higher accuracy of prediction

Experiment



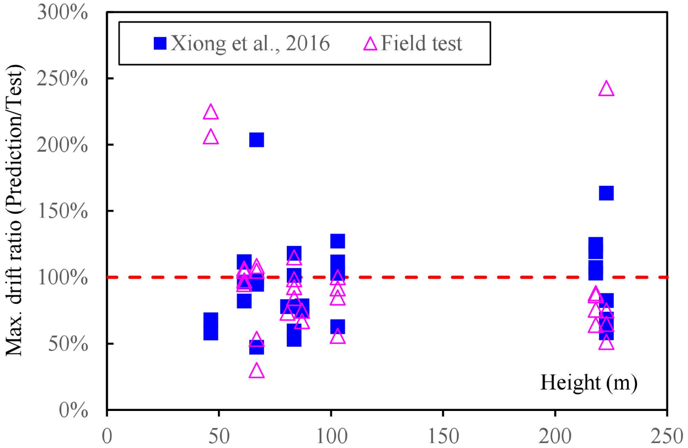






Agree well with experiments

Monitoring

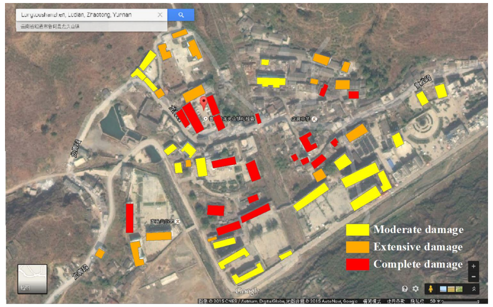


Error of maximal drift:

-4.6% (Proposed method)

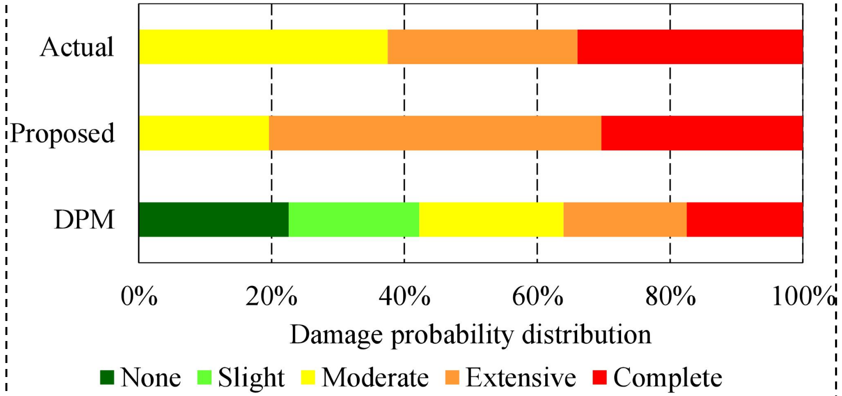
-2.8% (Period updated)

Compared with DPM



Actual damage of Longtoushan Town

Ludian Earthquake (M 6.5), 2014, China



More accurate than the traditional DPM method

(DPM: Damage Probability Matrices)

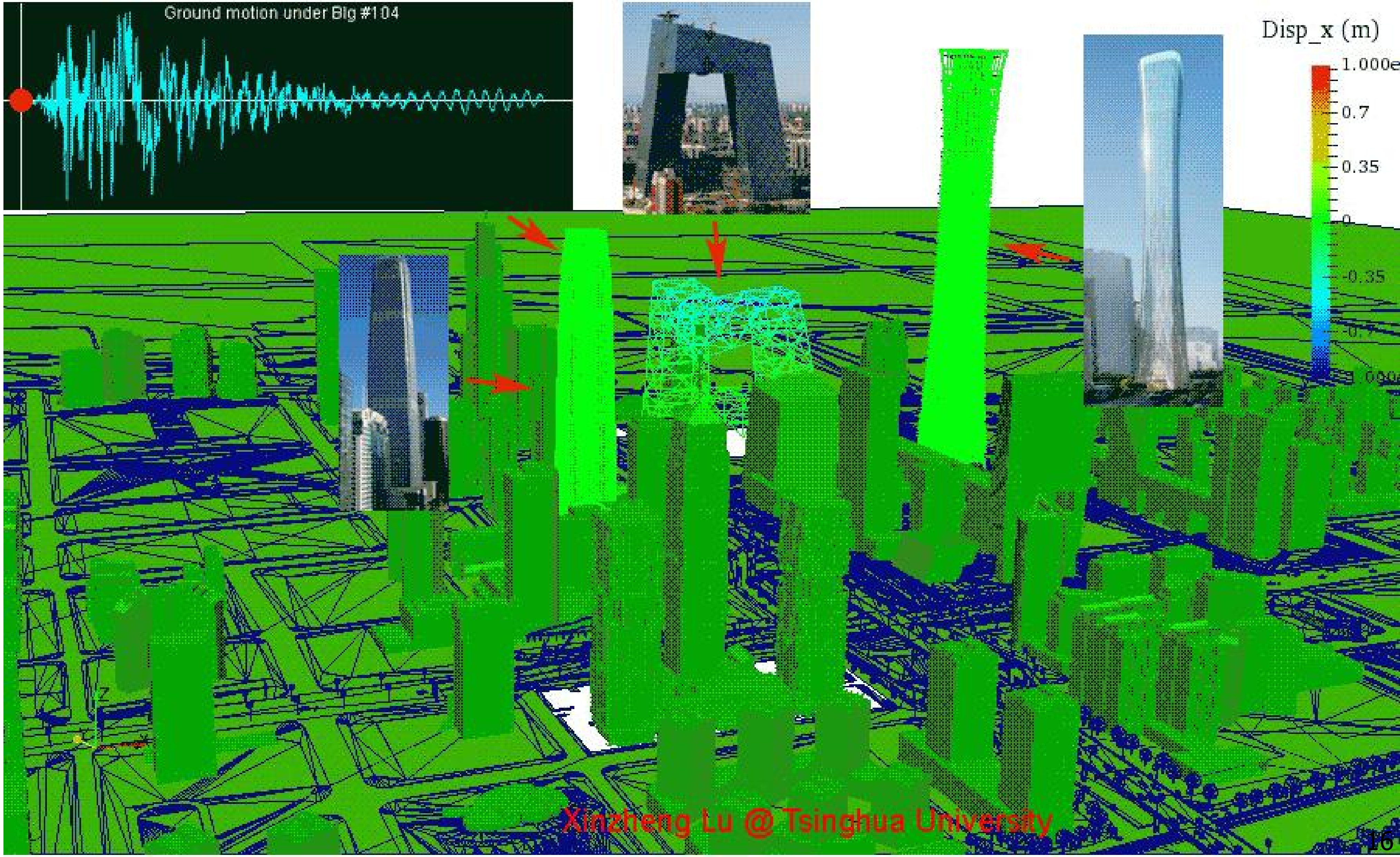
Lu XZ, Guan H, Earthquake Disaster Simulation of Civil Infrastructures: From Tall Buildings to Urban Areas (2nd Ed.), Singapore: Springer, 2021.

3.2 High-fidelity visualization of seismic response: **3D visualization**

3D visualization of Beijing CBD

Scenario: 1679 Sanhe-Pinggu M8.0 Earthquake

Many tall buildings under moderate damage, very difficult to repair



3.2 High-fidelity visualization of seismic response: AR visualization

AR visualization of New Beichuan City, Sichuan Province

Scenario: 2008 Wenchuan M8.0 Earthquake

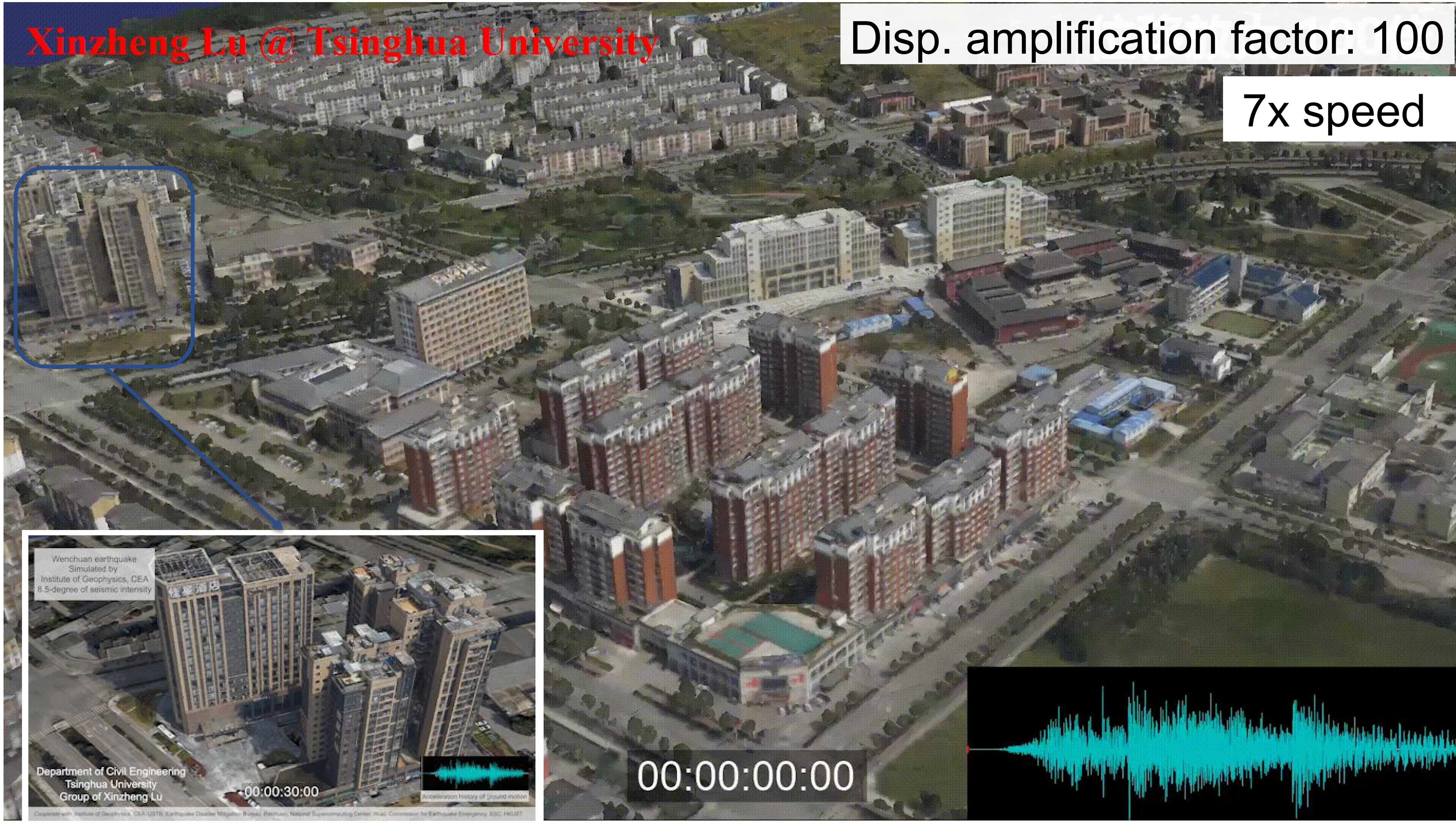
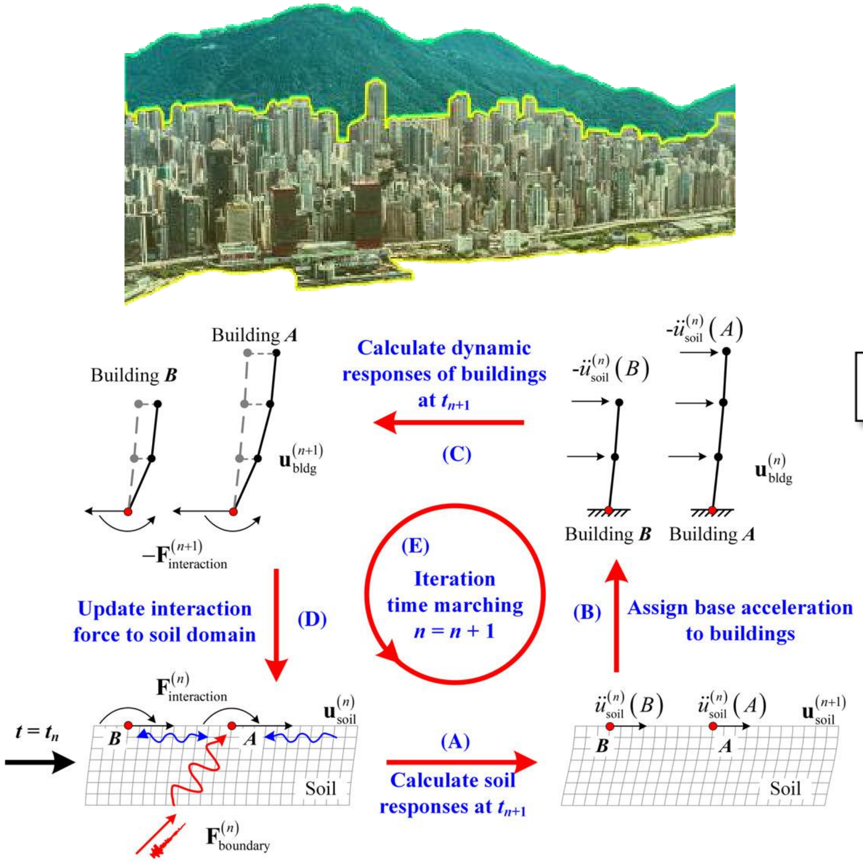
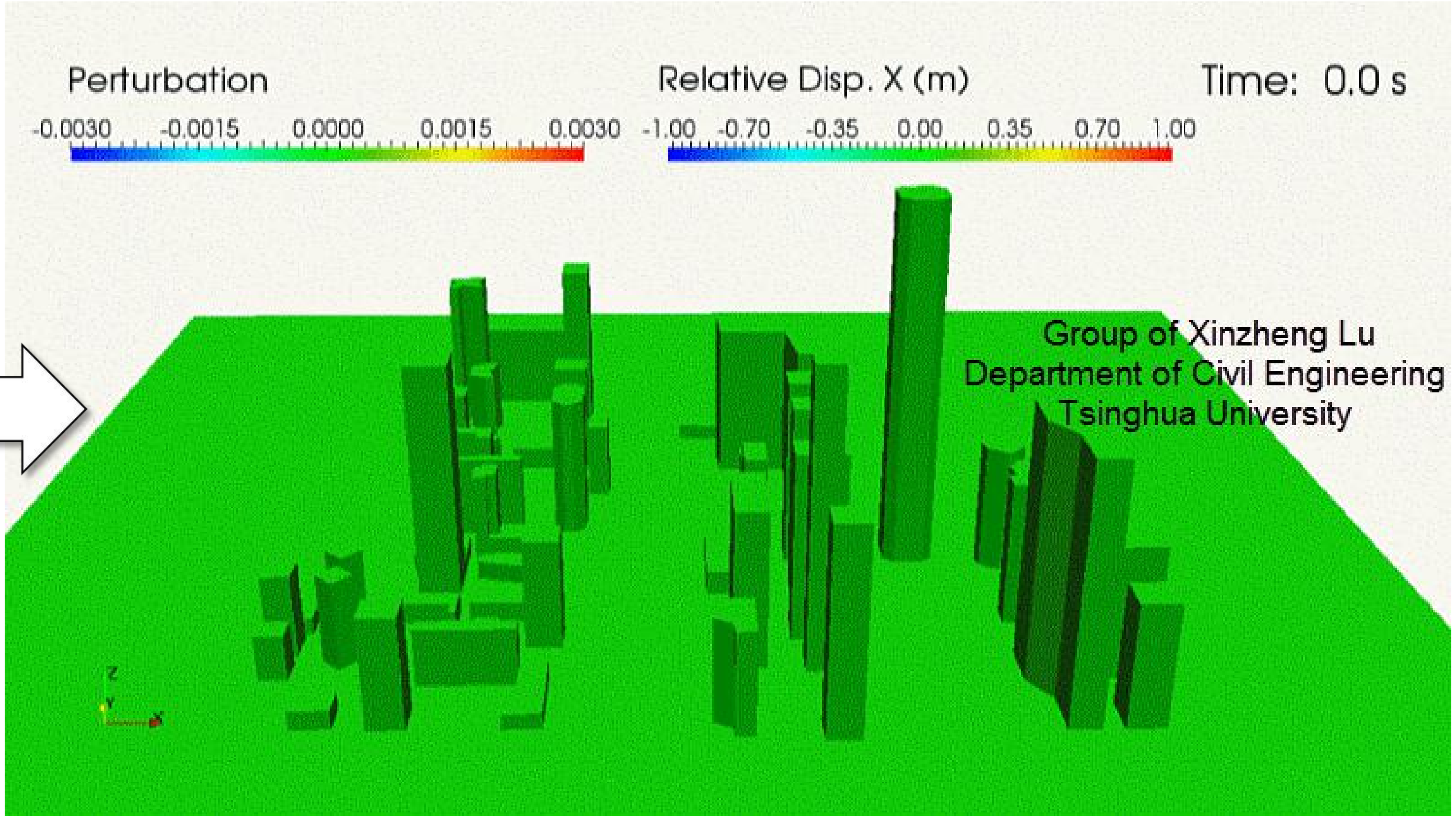


Photo-realistic visualization of seismic dynamic responses of urban building clusters based on oblique aerial photography, Advanced Engineering Informatics, 2020

Site-city interaction





"Global" interaction between all the buildings in a city and its subsoil

A numerical coupling scheme for nonlinear time-history analysis of buildings on a regional scale considering site-city interaction effects, Earthquake Engineering & Structural Dynamics, 2018

3.3 Typical applications

Before Earthquake

After Earthquake

City-scale nonlinear THA

Loss & repair

Falling debris

Evacuation

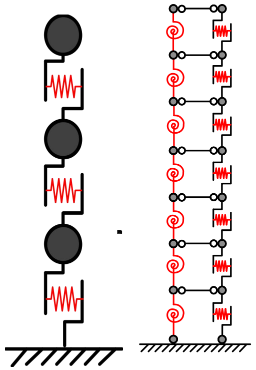
…

Urban planning, Disaster preparation

Emergency response

3.3.1 Seismic loss assessment

City-scale NLTHA



MDOF model

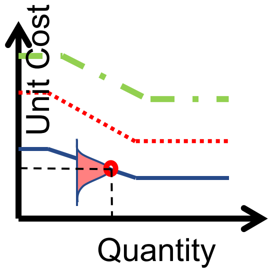
EDPs

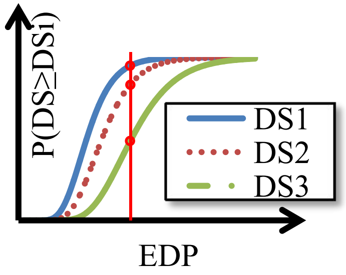
Engineering demand parameters

PFA, PFV, IDR residual drift

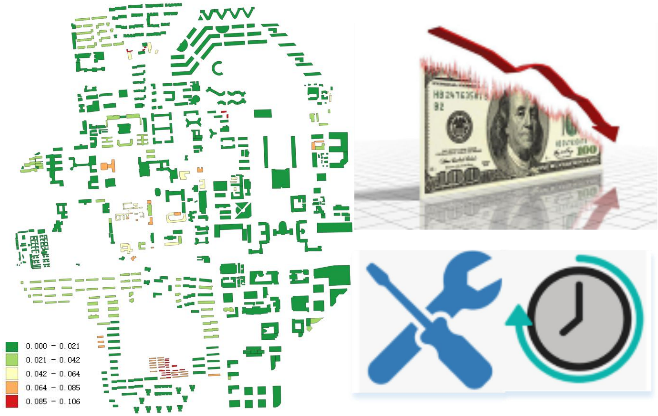
Performance Groups

Performance models





FEMA P-58 consequence functions and fragility curves

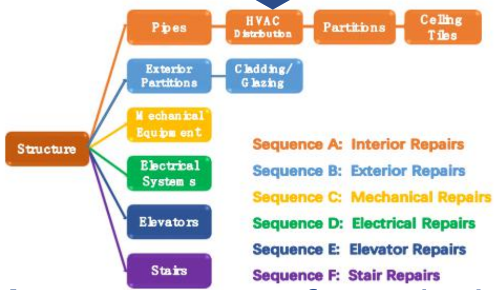


Economic loss, repair time

3.3.2 Post-earthquake recovery simulation

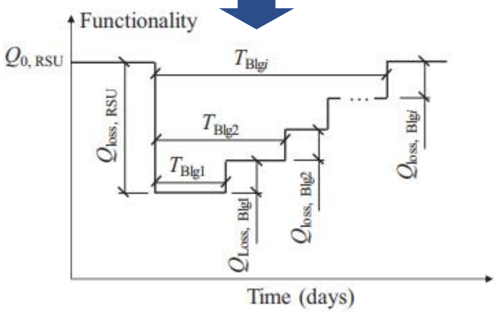
- Resilience recovery simulation of Beijing City
  - 68,930 residential buildings under an M8.0 earthquake

Building residual functionality

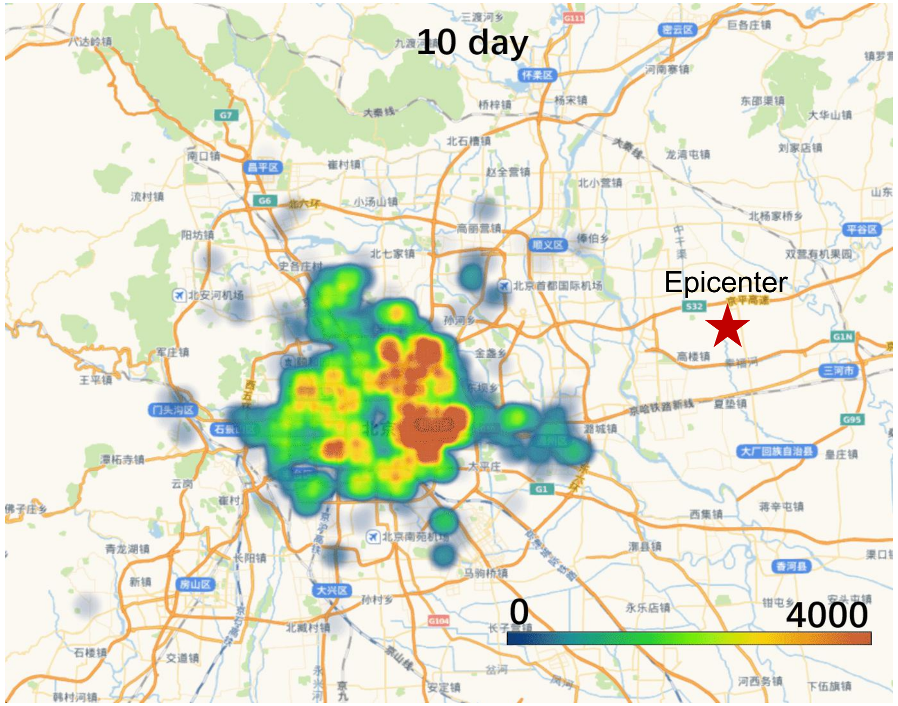


Courtesy Almufti et al.

Repair sequences of a typical building



Recovery curve of a repair-scheduling unit



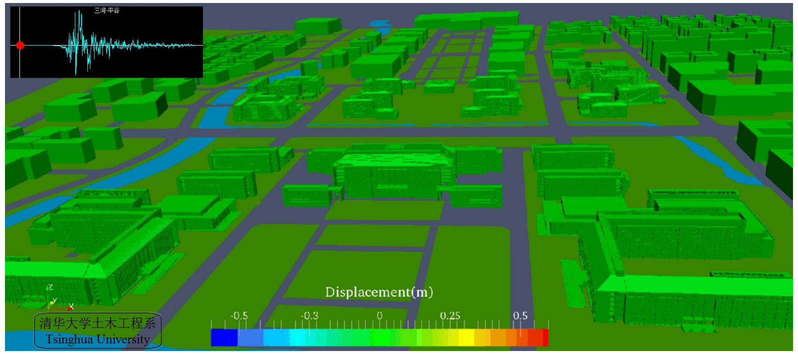
Temporal evolution of the **worker distribution**

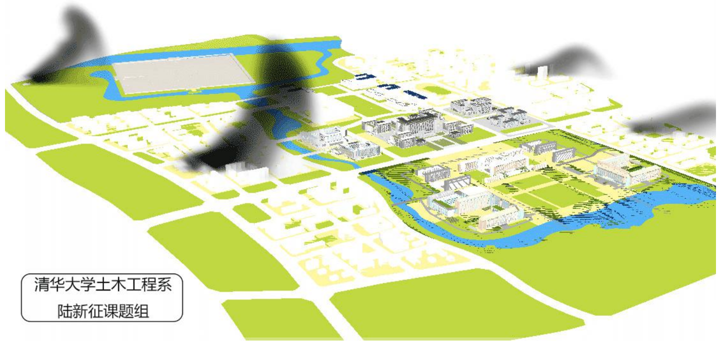
Detailed repair time and recovery process

Framework for city-scale building seismic resilience simulation and repair scheduling with labor constraints driven by time-history analysis, Computer-Aided Civil and Infrastructure Engineering, 2019

3.3.3 Applications: Pre-EQ damage prediction


应用证明



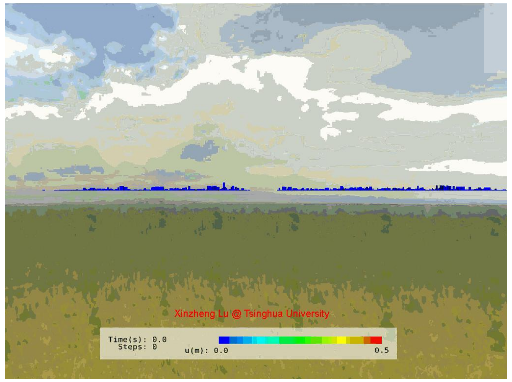



技 术 服 务 合 同

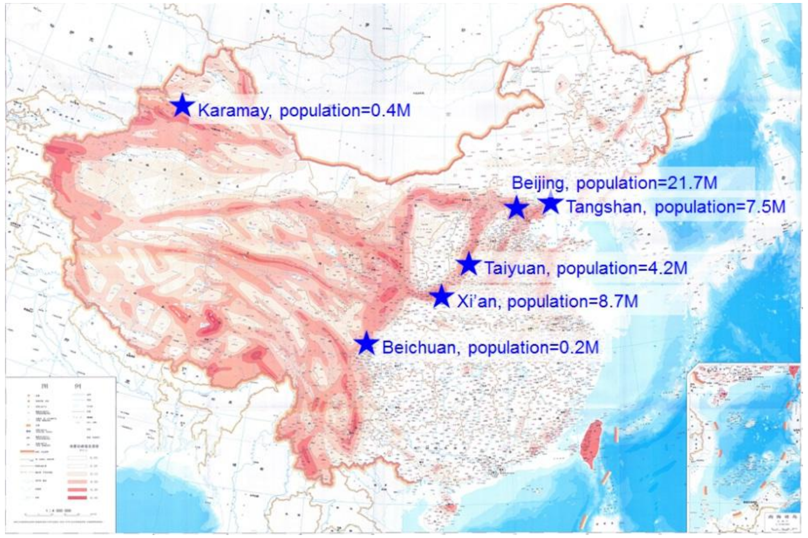
Beijing 2nd Adm. Center (2017), Tongzhou & Daxing Districts (2018, 2019)

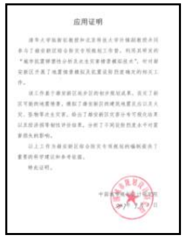

太原市防震减灾局

应用证明



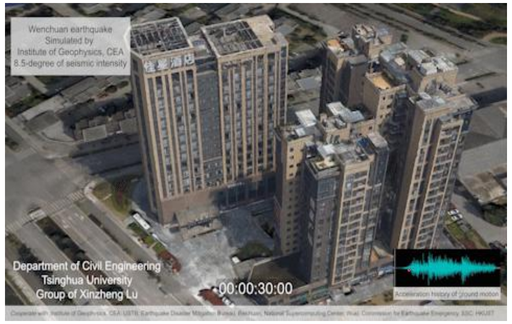
Taiyuan (2017)



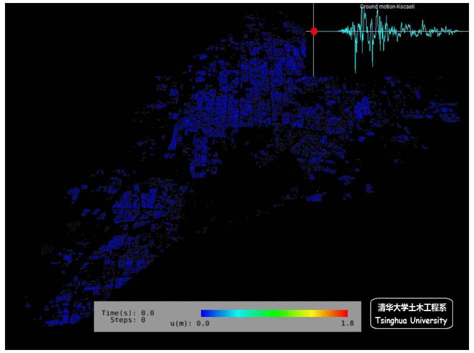

应用证明

Xiong'An (2017)


绵阳市防震减灾局



New Beichuan (2018)

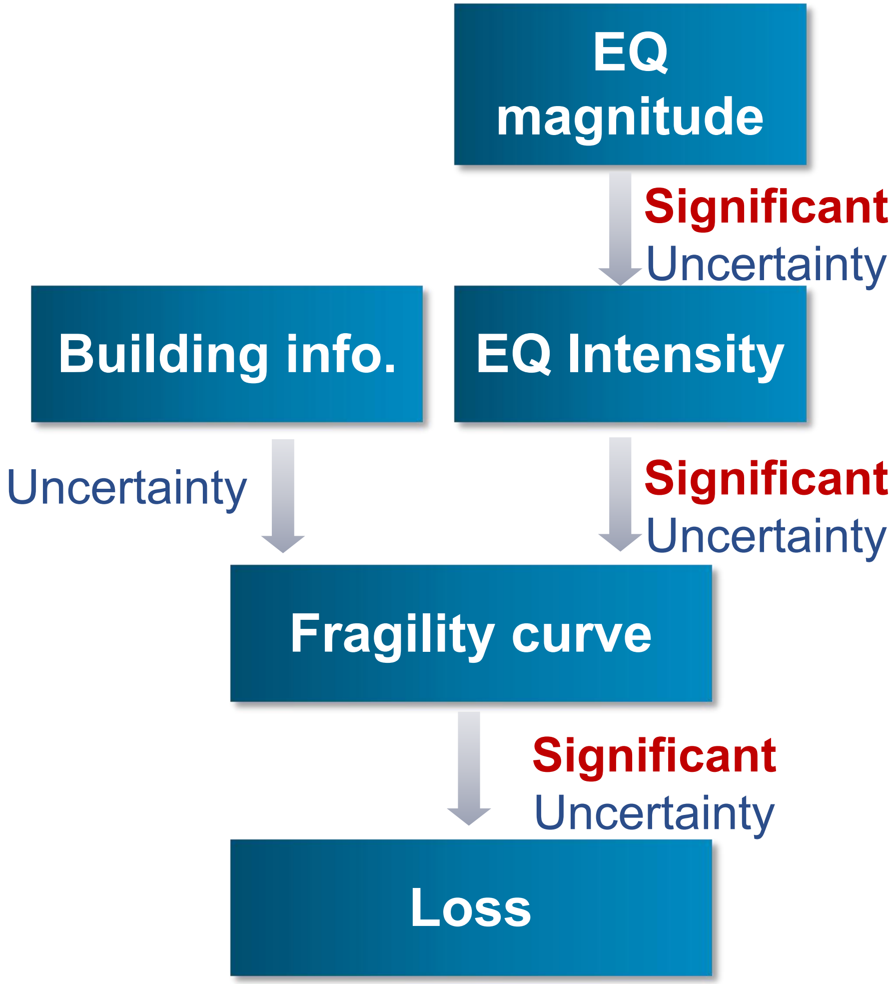



应用证明

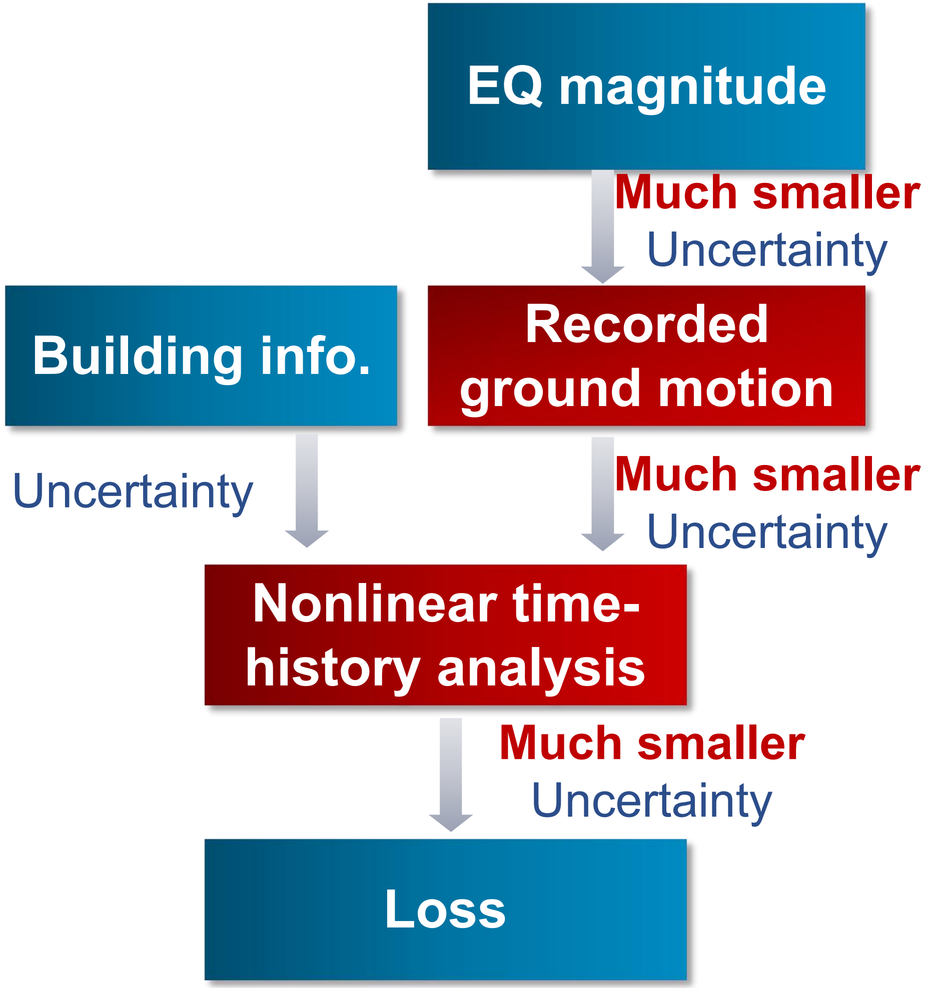
Tangshan (2016)

3.3.4 Real-time post-EQ assessment

Conventional method



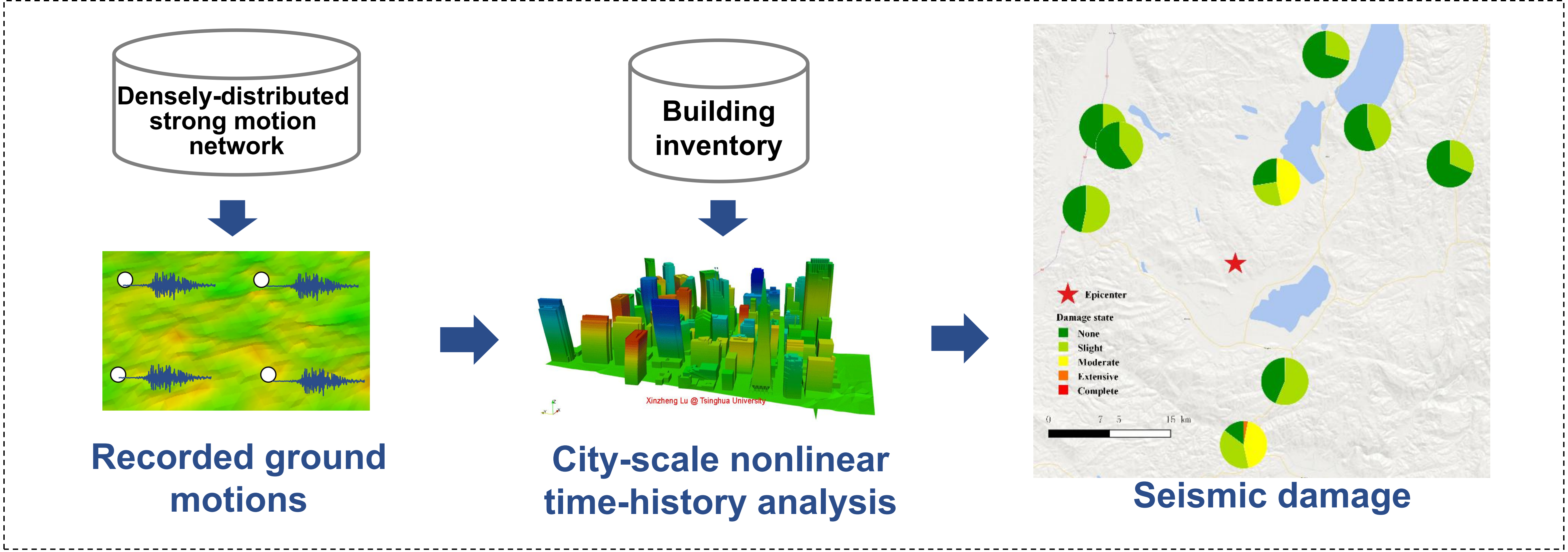
Proposed method



Real-time city-scale time-history analysis and its application in resilience-oriented earthquake emergency responses, Applied Sciences, 2019

3.3.4 Real-time post-EQ assessment

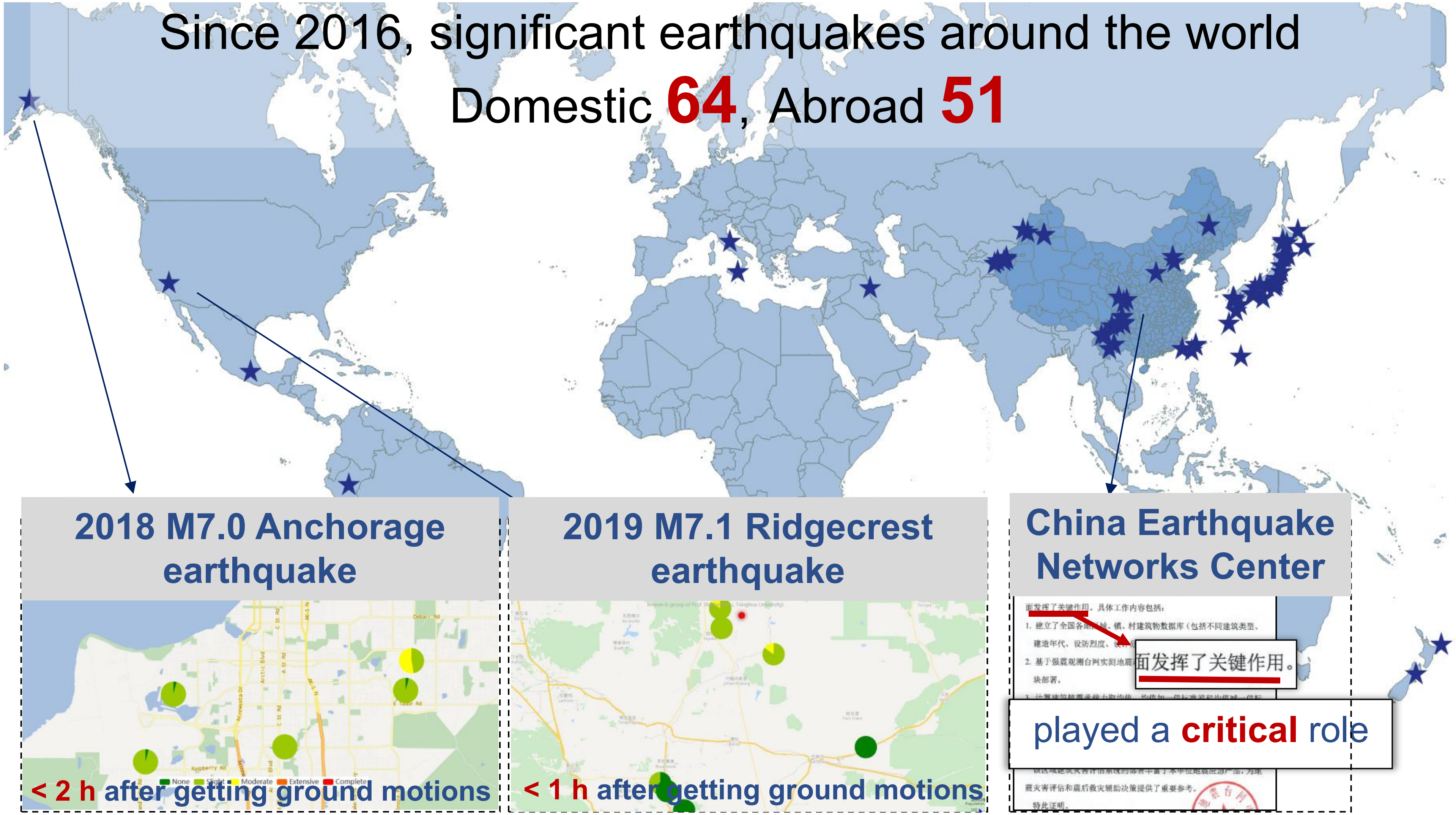
- **R**eal-time **E**arthquake **D**amage **A**ssessment using **C**ity-scale **T**ime-History Analysis (**RED-ACT**)



Real-time city-scale time-history analysis and its application in resilience-oriented earthquake emergency responses, Applied Sciences, 2019

3.3.4 Real-time post-EQ assessment

- China, USA, Japan, Italy, New Zealand, etc.



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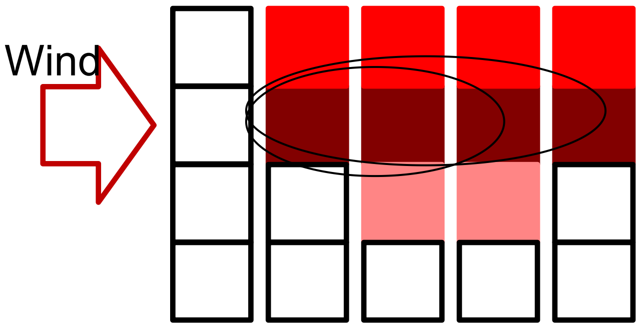
4.1 Physics-driven fire simulation of communities

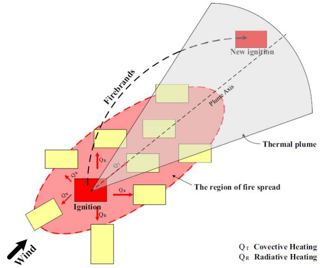
Empirical fire spread model



Examples: Hamada 1975, FEMA 2012

Features	
▪ Suitable for different regions	✗
▪ Consider building state (e.g., seismic damage)	✗
▪ Consider weather conditions	✗
▪ High-fidelity visualization	✗

Physics-driven fire simulation



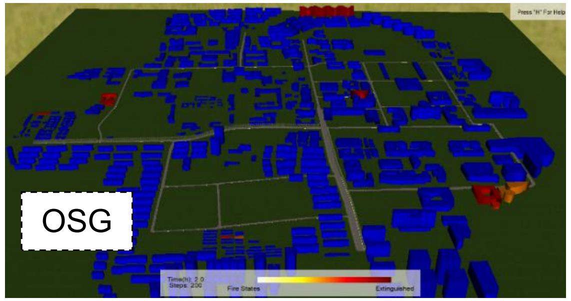
Fire spread (Zhao 2010)

Thermal Plume + Radiation

Fire spread results

- Ignition time
- Burning duration
- Burned area
- · · ·

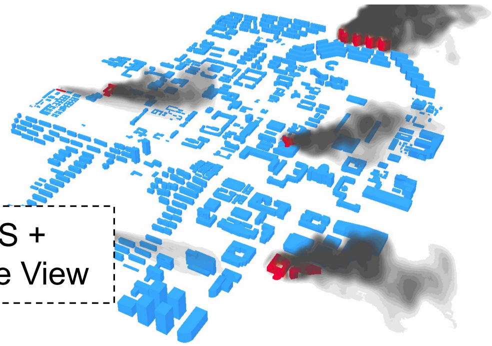
High-fidelity visualization



Fire spread visualization

Physics-driven smoke simulation

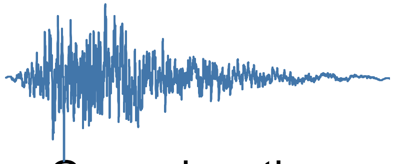
FDS + Smoke View



Smoke visualization

4.1 Physics-driven fire simulation of communities

- Physics-driven simulation of **fire following earthquake (FFE)**



Ground motion

Physics-driven building model

- Building seismic damage

Physics-driven earthquake simulation

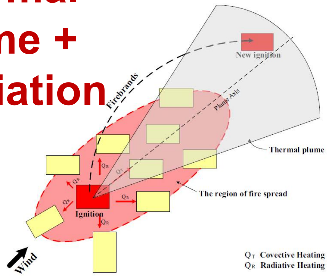
$$P(R_{1i}) = P(M) \times P(F_K / M) \times P(G) \times P(D_J)$$

Initial ignited building

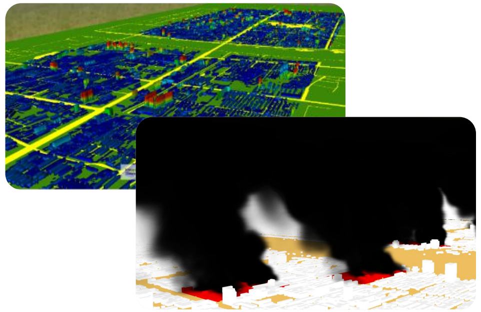
(Ren and Xie 2004)

Ignition model

Thermal Plume + Radiation



Physics-driven FFE model



Fire spread and smoke visualization

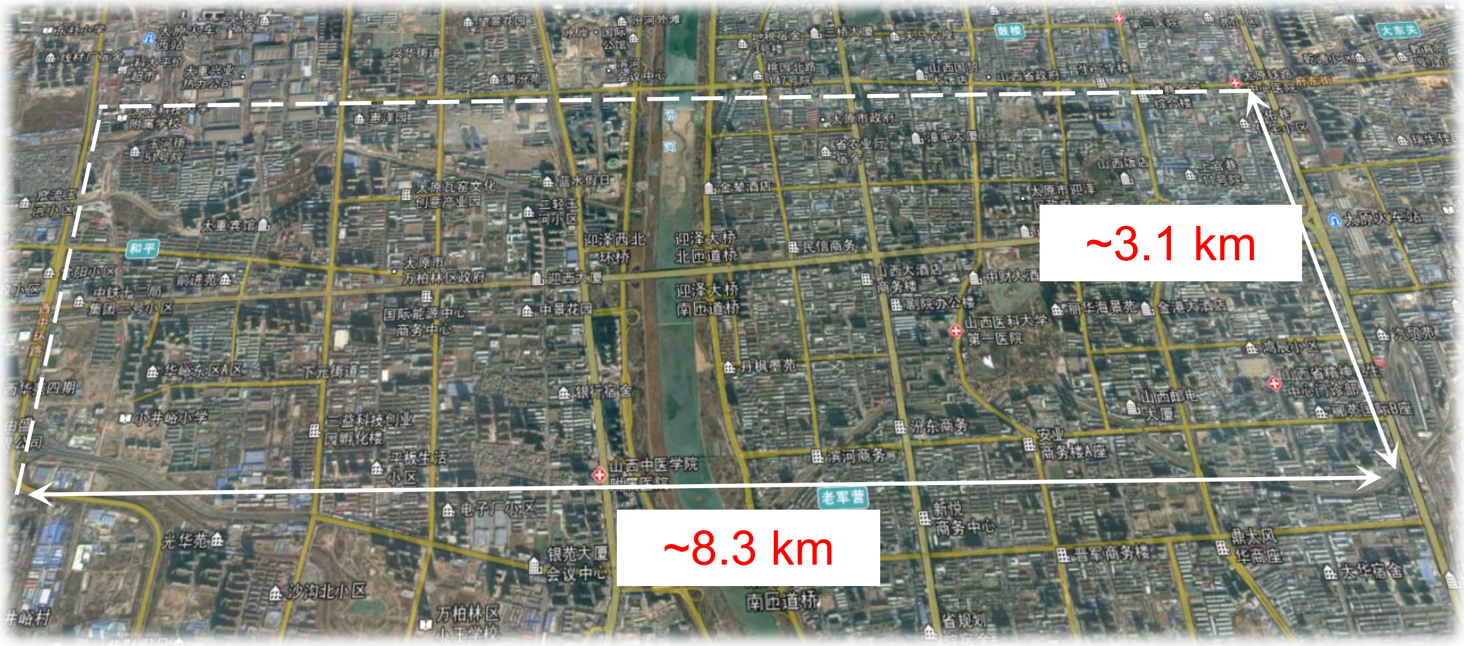
Physics-driven FFE simulation

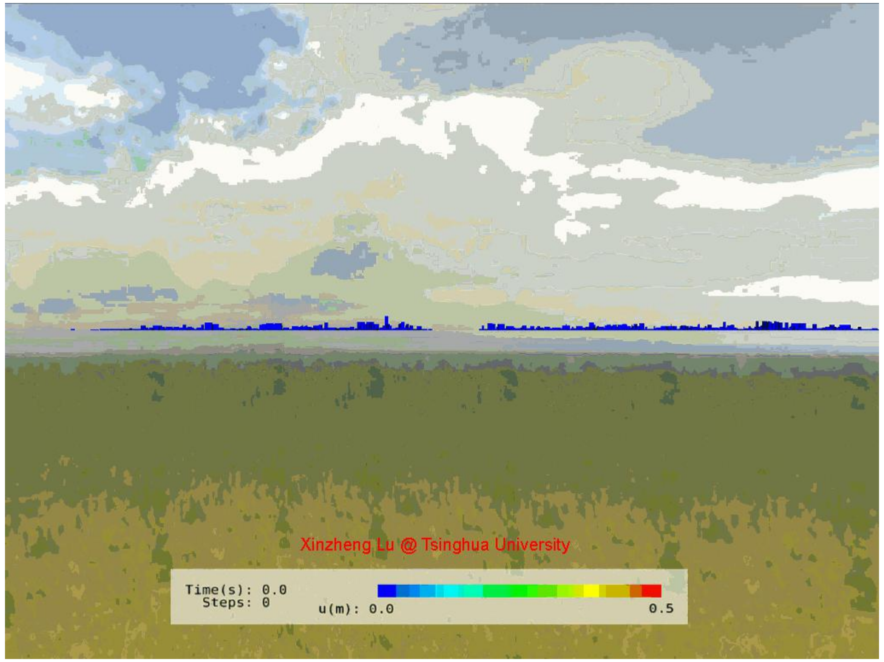
Features	
▪ Suitable for different regions	√
▪ Consider building state (e.g., seismic damage)	√
▪ Consider weather conditions	√
▪ High-fidelity visualization	√

Physics-based simulation and high-fidelity visualization of fire following earthquake considering building seismic damage, Journal of Earthquake Engineering, 2017

4.2 Case study: Taiyuan City, Fire follow earthquake

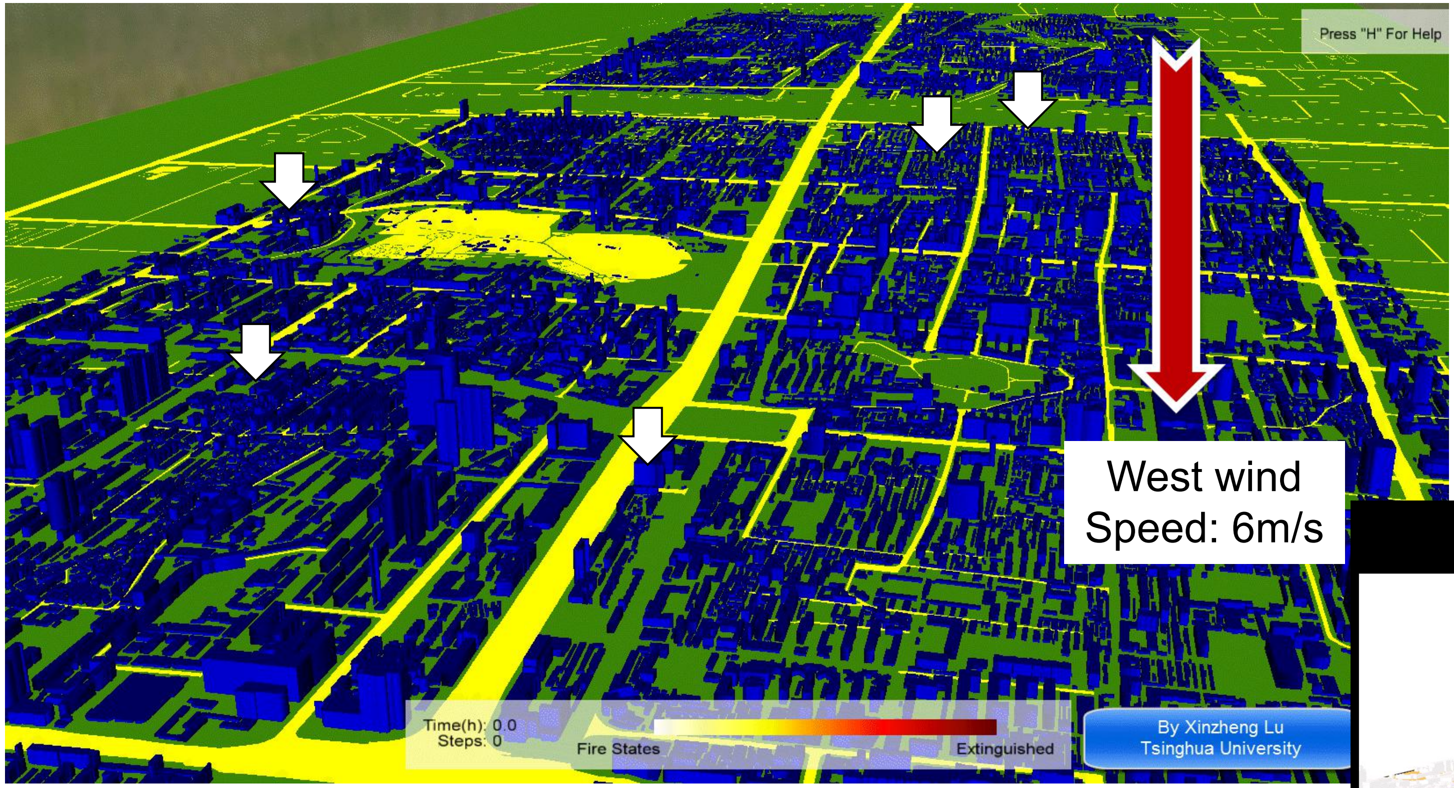
- Central Taiyuan City
- 26 km^2, **44,152** buildings
- Design based earthquake level





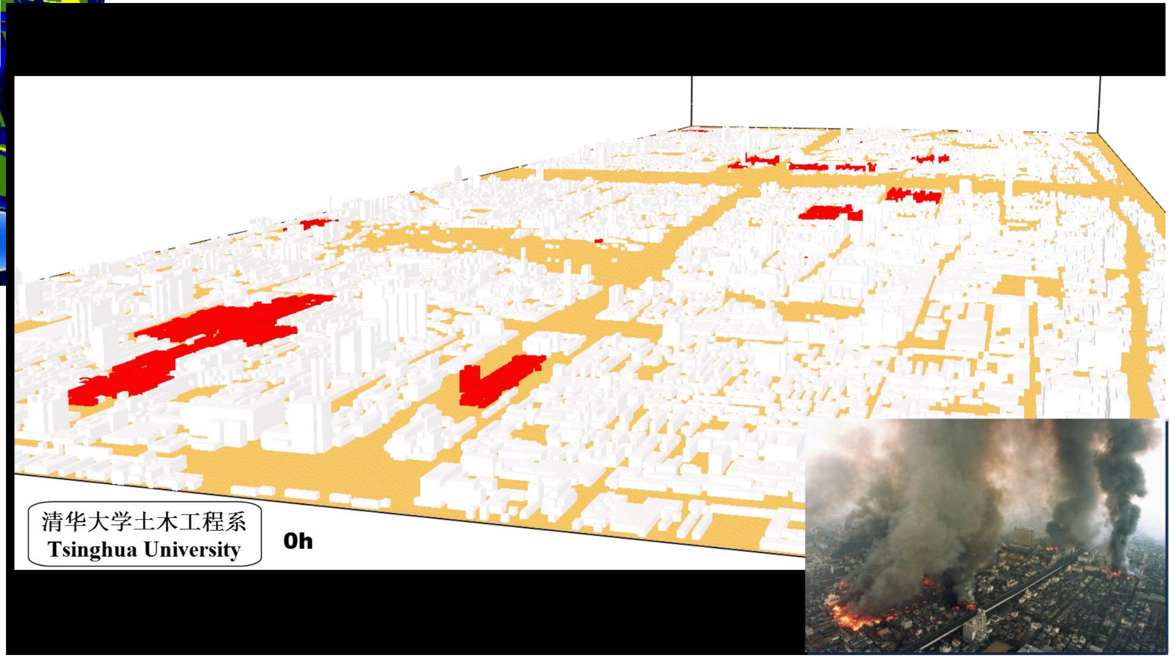
Physics-based simulation and high-fidelity visualization of fire following earthquake considering building seismic damage, Journal of Earthquake Engineering, 2017

4.2 Case study: Taiyuan City, Fire follow earthquake



Fire spread visualization

Features	
▪ Suitable for different regions	√
▪ Consider seismic damage	√
▪ Consider weather conditions	√
▪ High-fidelity visualization	√

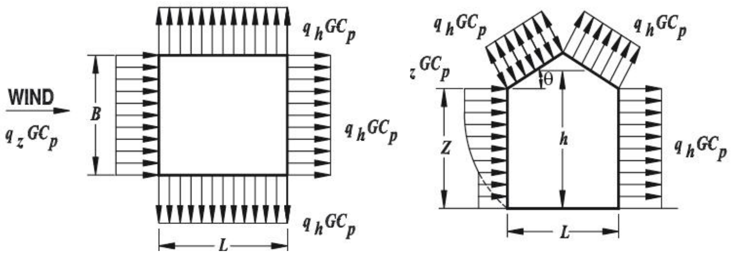


Smoke visualization

Physics-based simulation and high-fidelity visualization of fire following earthquake considering building seismic damage, Journal of Earthquake Engineering, 2017

4.3 Physics-driven wind simulation of communities

Empirical model



Example: ASCE 7-10

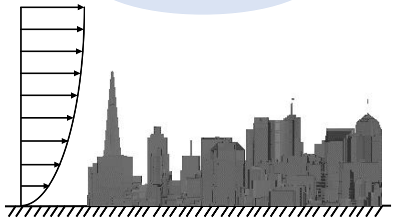
Features	
▪ Consider complex building configuration	×
▪ Obtain wind data at any location	×
▪ Can be used to model the entire community	×
▪ Model different wind hazard scenarios	×

Physics-driven building vibration simulation
City-scale time-history analysis

➕

Physics-driven wind simulation
City-scale large eddy simulation

Step 1



CFD model

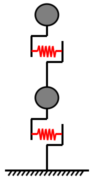
LES

Urban flow
- Grid coordinates
- Wind pressure
- Wind speed

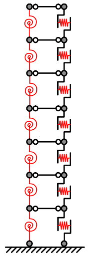
Step 2

Time history of wind load on each story

Step 3



MDOF shear model

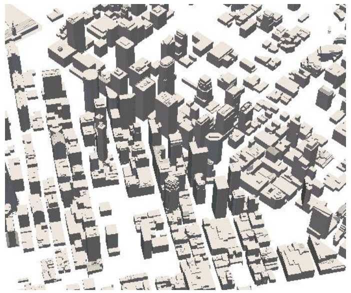


MDOF flexural-shear model

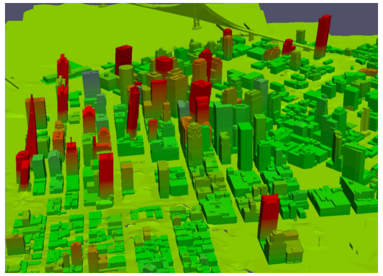
City-scale THA

Time history of building response

Step 4

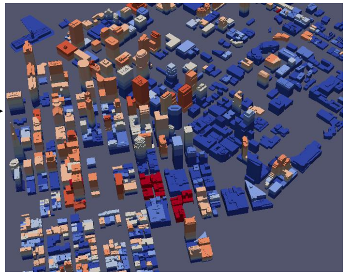


3D urban model for visualization

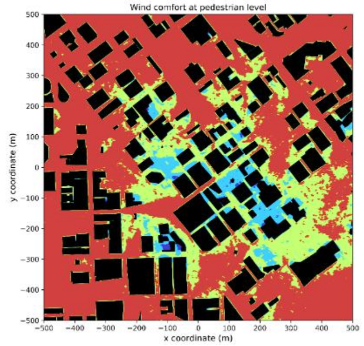


High-fidelity visualization of building response

Step 5



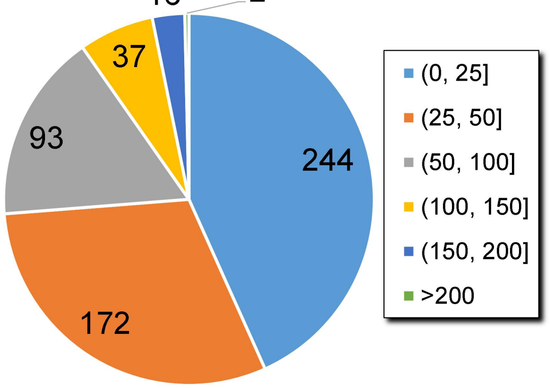
Occupant comfort assessment



Wind comfort assessment at pedestrian level

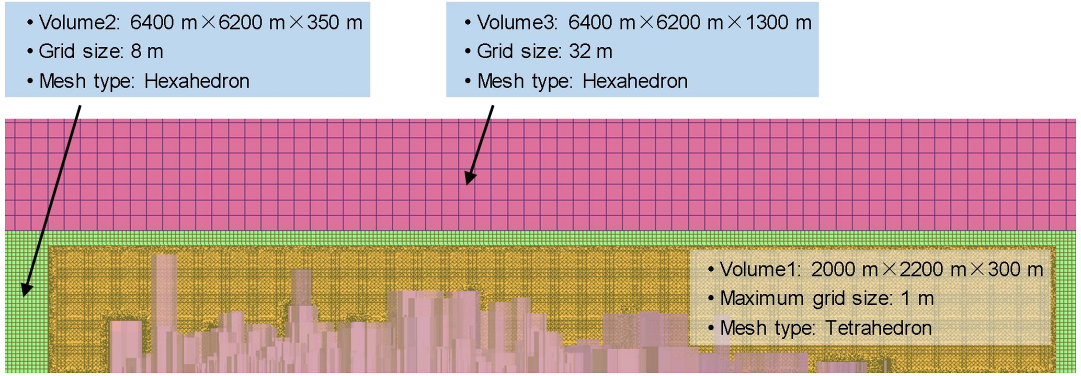
4.4 Case Study: San Francisco Downtown, Wind

- **564 buildings**
- Area: **1950 m × 2120 m**
- Maximum height: **252 m**



Distribution of building height

- Mesh scheme (6400 × 6200 × 1650 m^3)



180 million cells

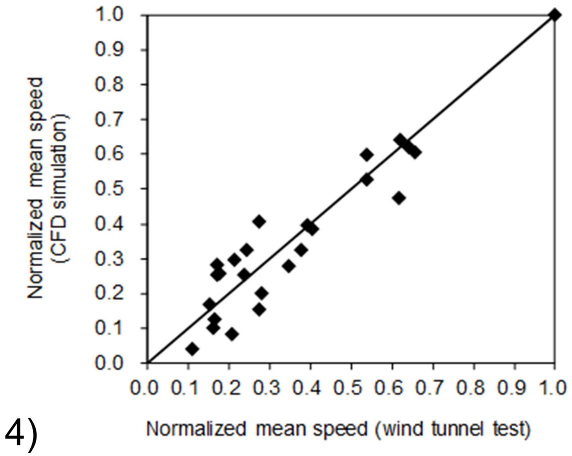
- Hazard scenario

✓ Inflow: $U(z) = 33.76\, z^{0.143}$ **(MRI = 700 Years)**

Time step: 0.01 s

- CFD validation

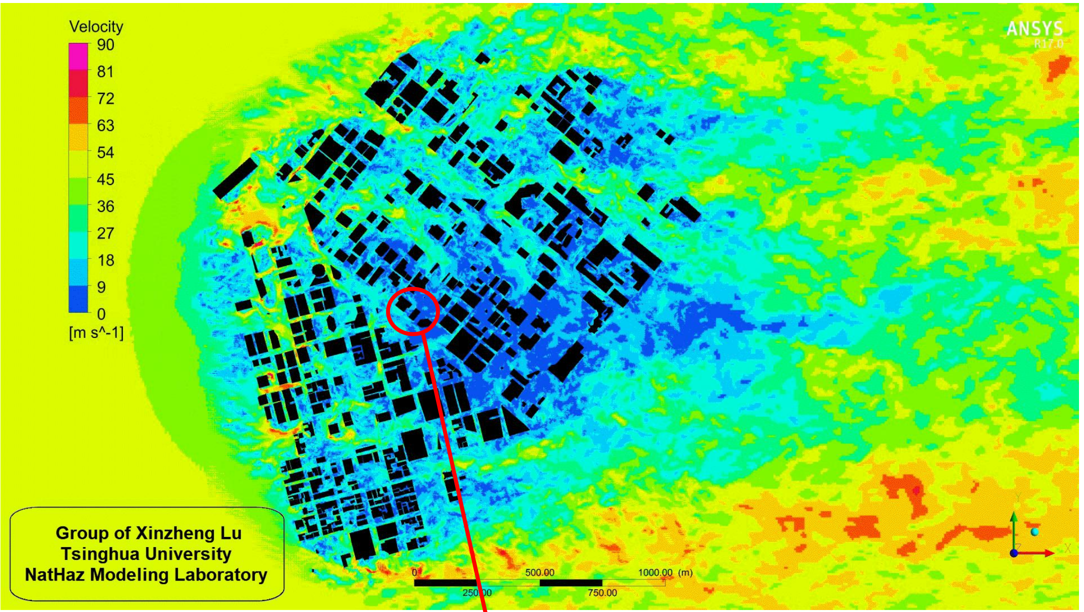
Wind tunnel test by UCB (Kim 2014)



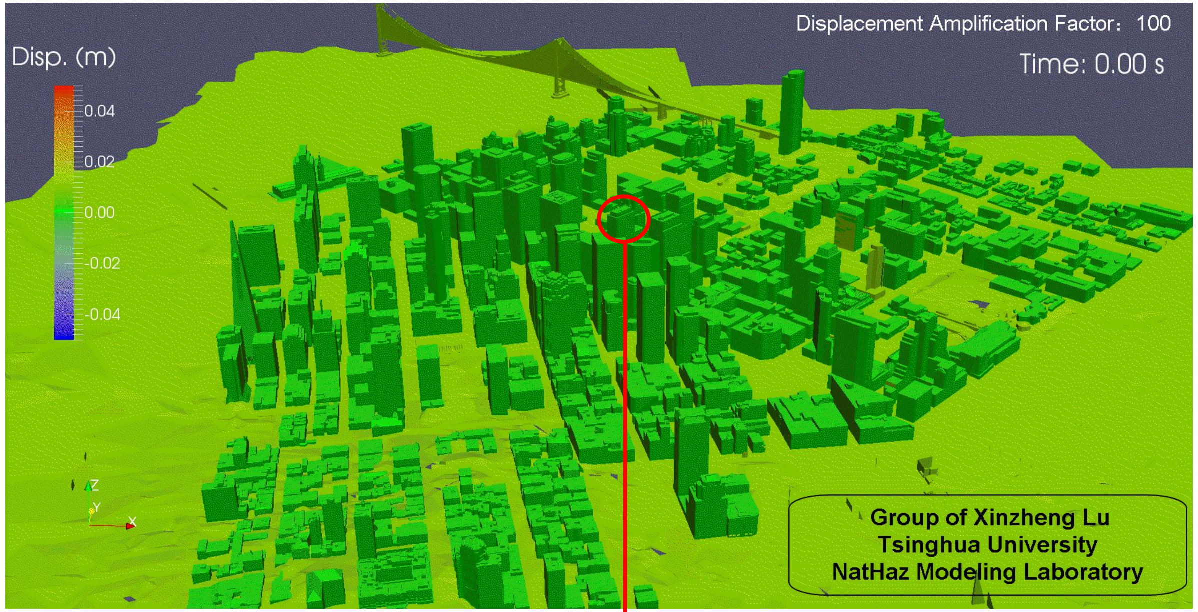
Agree well

4.4 Case Study: San Francisco Downtown, Wind

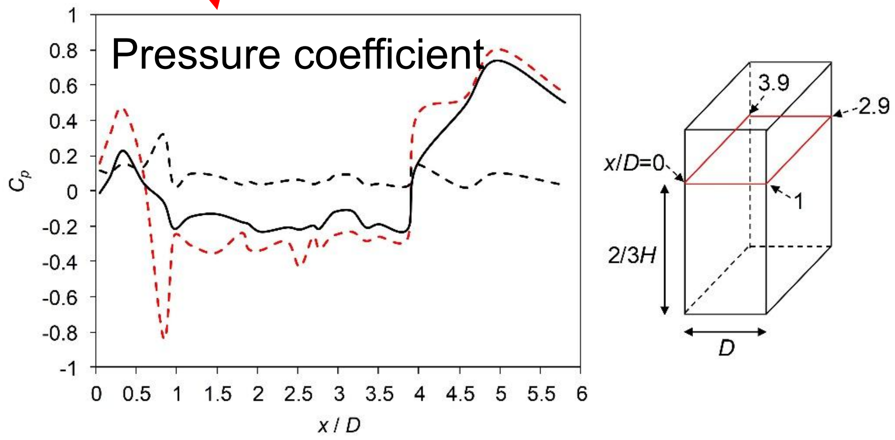
Wind speed at a height of 20 m

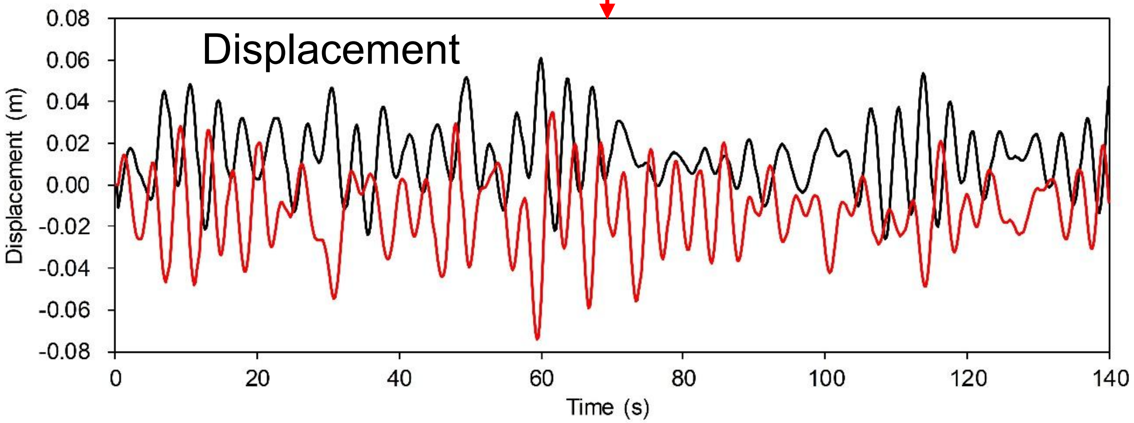


Wind-induced motion of buildings



Detailed results of specific building

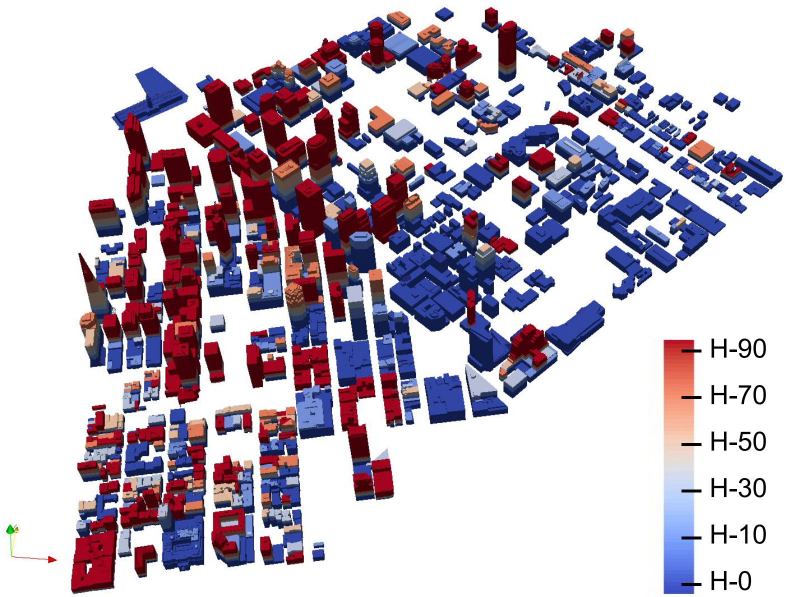




Computational simulation of wind-induced motion of tall buildings in cityscapes. The 15th International Conference on Wind Engineering (ICWE15). 2019, Beijing, China.

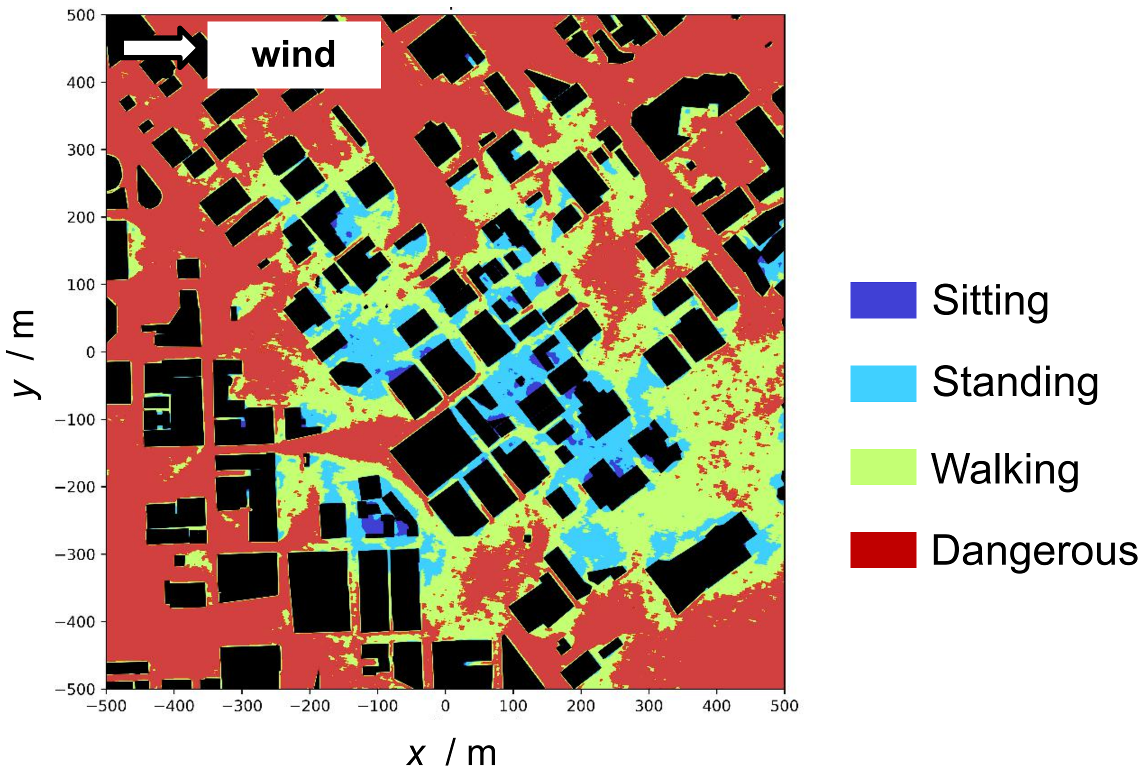
4.4 Case Study: San Francisco Downtown, Wind

Occupant comfort



Among the 55 buildings over 100 m, **87.3%** of the buildings indicate an occupant comfort quality of **H-90** in the top story.

Pedestrian wind comfort



Sitting: 18.37%	Walking: 16.08%
Standing: 22.26%	Dangerous: **43.29%**

Computational simulation of wind-induced motion of tall buildings in cityscapes. The 15th International Conference on Wind Engineering (ICWE15). 2019, Beijing, China.

4.5 Physics-driven COVID-19 simulation of communities

- **January 2020, in response to the shortage of medical resources, Chinese cities began to build temporary hospitals**

e.g., Huoshenshan Hospital

"A race for life!"

It took only 10 days from the order of design to the completion of the construction.

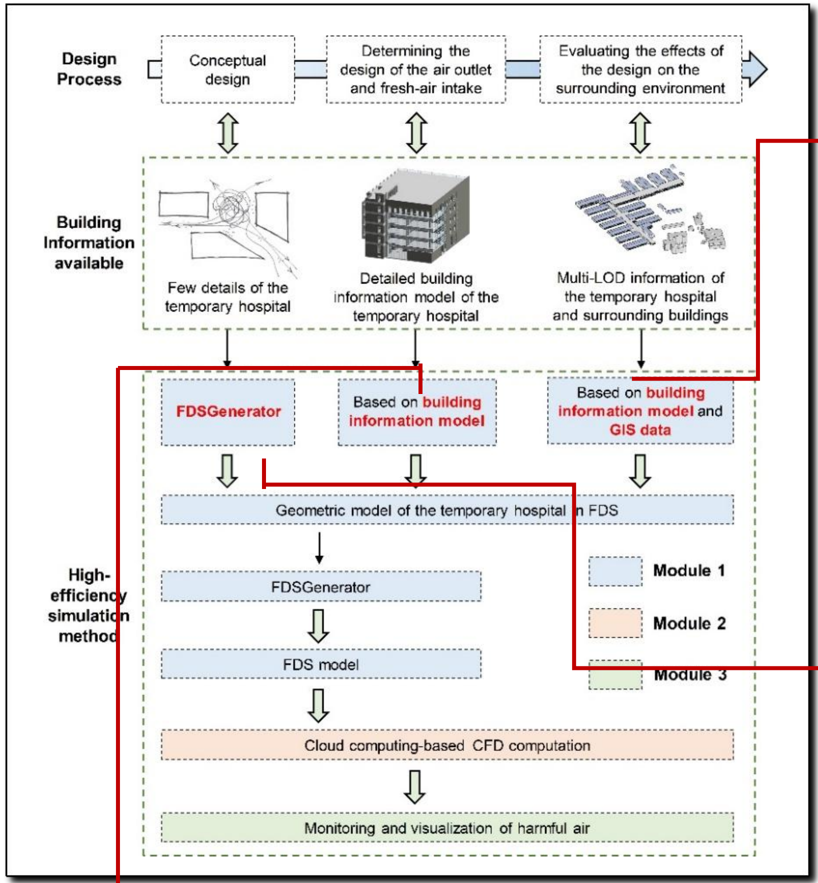
How to quantitatively evaluate the infection risk caused by the harmful air from temporary hospitals with high efficiency and accuracy ?

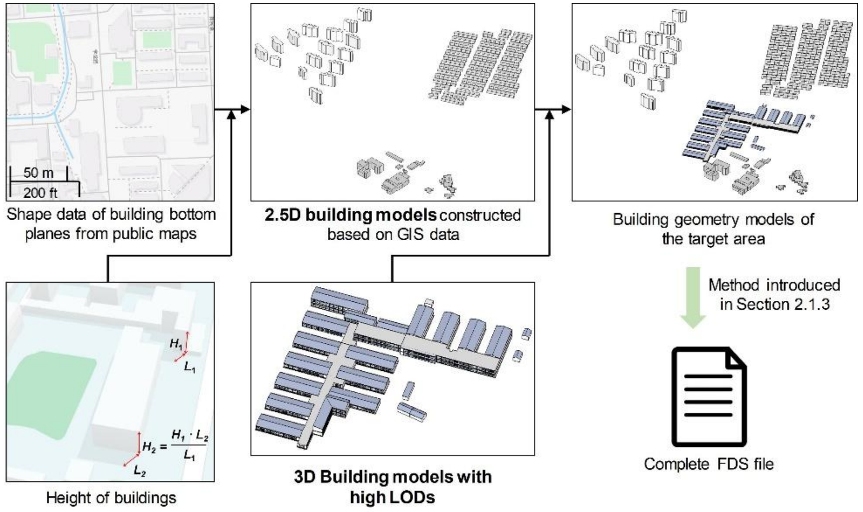
High-efficiency simulation framework to analyze the impact of exhaust air from COVID-19 temporary hospitals and its typical applications, Applied Sciences, 2020

4.5 Physics-driven COVID-19 simulation of communities

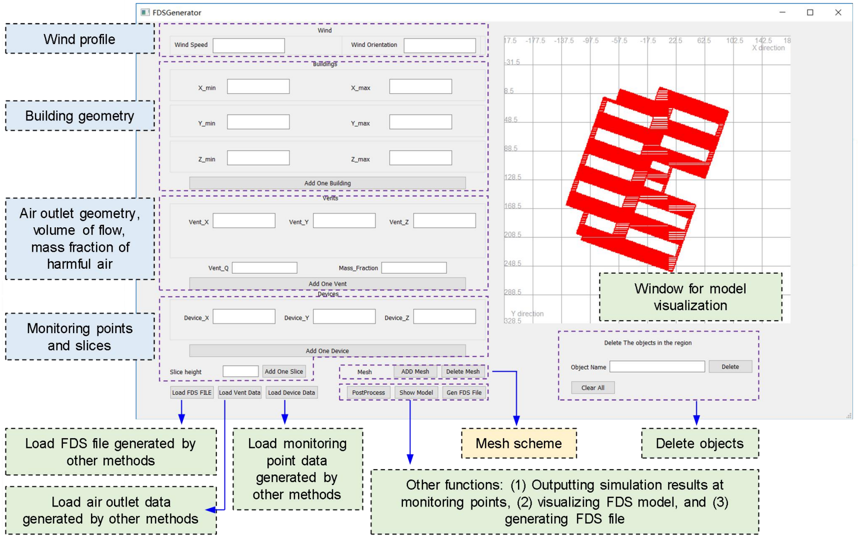
From multi-level-of-details CIM to CFD

Modeling and CFD simulation < 6 hours!



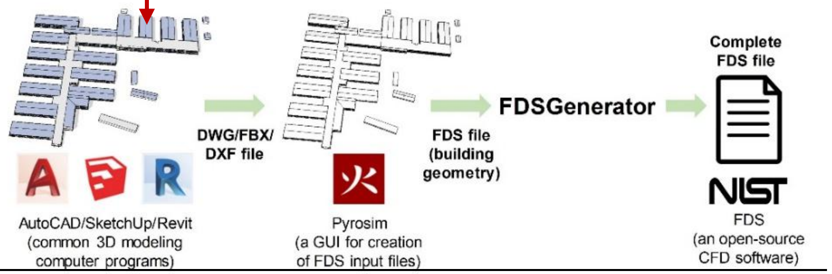


In the later design phase



In the conceptual design phase

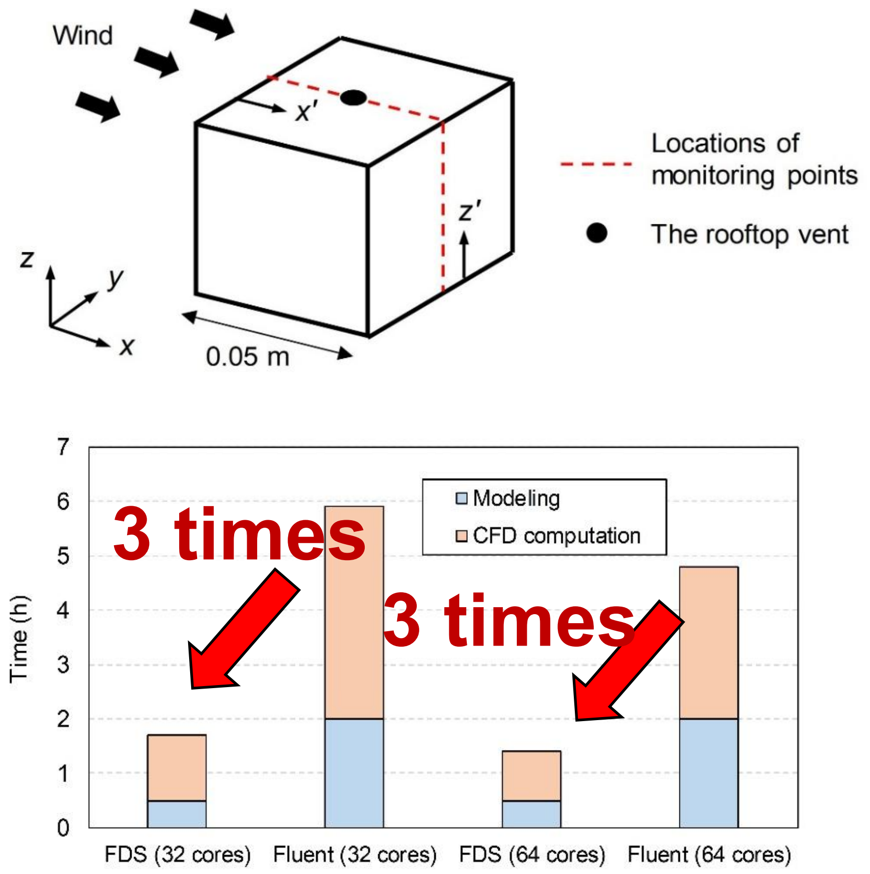
In the transition phase



High-efficiency simulation framework to analyze the impact of exhaust air from COVID-19 temporary hospitals and its typical applications, Applied Sciences, 2020

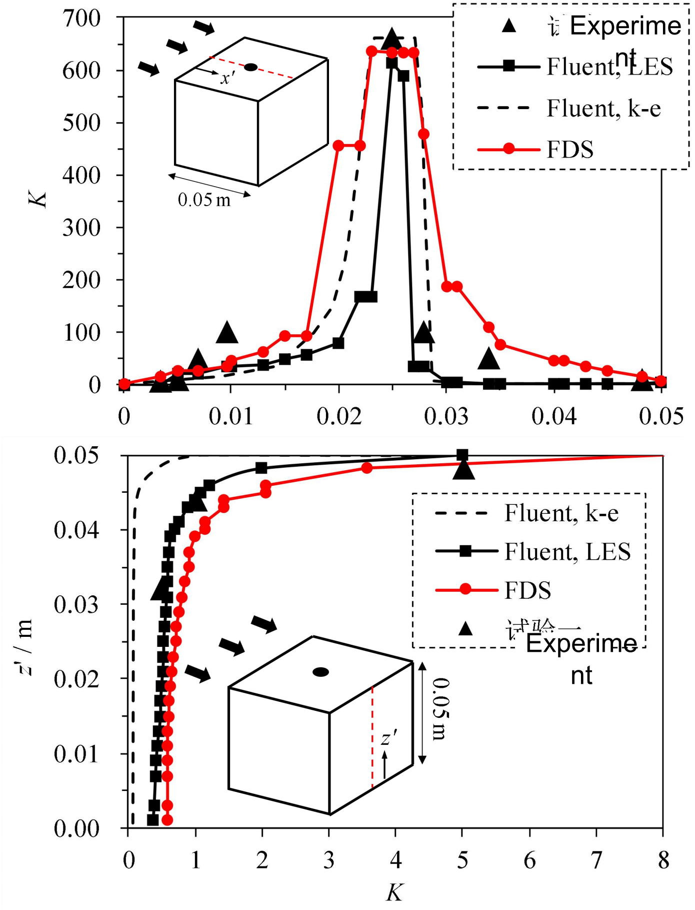
4.5 Physics-driven COVID-19 simulation of communities

Comparison of efficiency



The proposed method saves a considerable amount of time and money

Comparison of accuracy



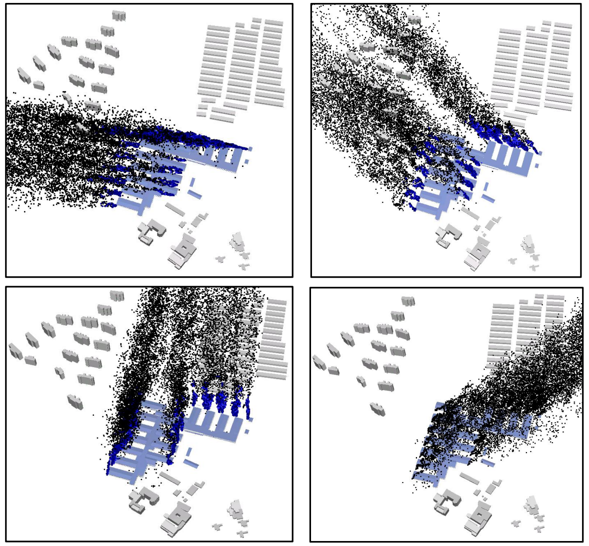
The simulation results agree well with the experiment results

High-efficiency simulation framework to analyze the impact of exhaust air from COVID-19 temporary hospitals and its typical applications, Applied Sciences, 2020

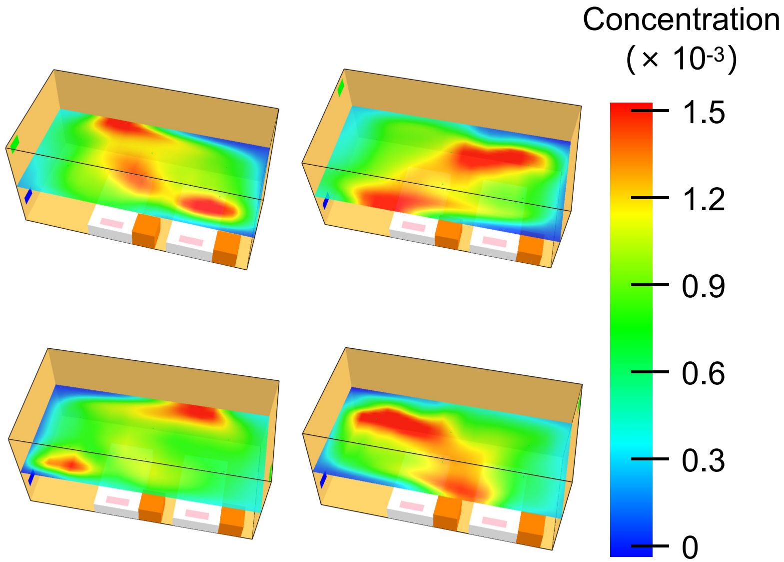
4.6 Applications

- **Huoshenshan hospital**

Jan. 28, 2020 (Wuhan)

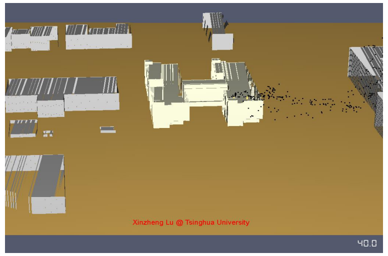


Outdoors: different wind directions

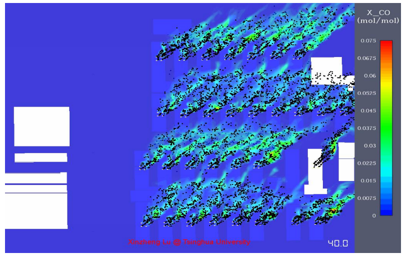


Indoor: different design schemes

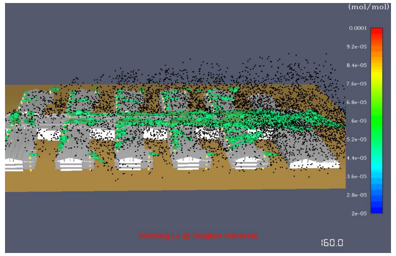
Jan. 29, 2020
Ditan hospital
(Beijing)



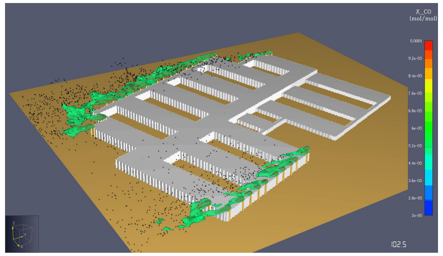
Jan.30, 2020
Leishenshan hos.
(Wuhan)



Feb.04, 2020
Xiaotangshan hos.
(Beijing)



Feb.14, 2020
3rd people's hos.
(Shenzhen)



Total number of sickbeds benefiting from the proposed method:

> 10,000

Concentration of the exhausted harmful air was reduced by 50% – 90%

High-efficiency simulation framework to analyze the impact of exhaust air from COVID-19 temporary hospitals and its typical applications, Applied Sciences, 2020

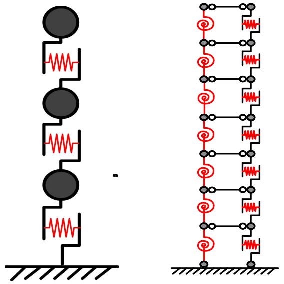
Outlines

1. Research Background
2. Multi-hazard simulation framework based on CIM
3. Physics-driven regional earthquake simulation
4. Physics-driven fire, wind/COVID-19 simulation of communities
5. Conclusions

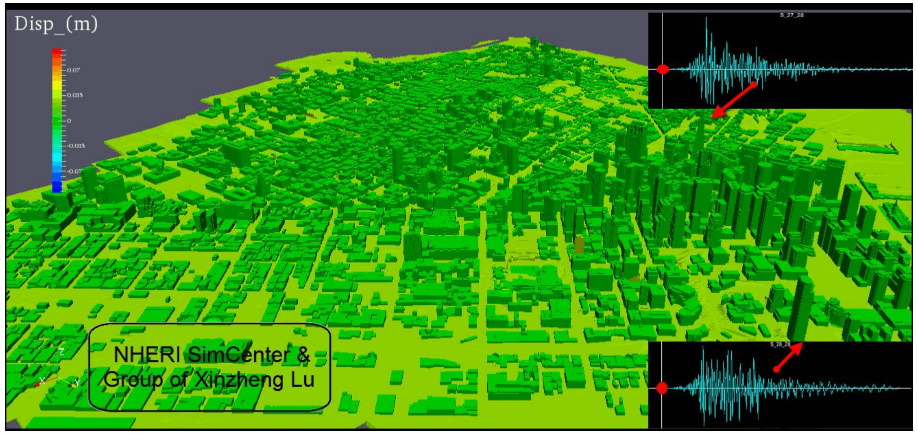
5 Conclusions

- Physics-driven disaster simulations: San Francisco

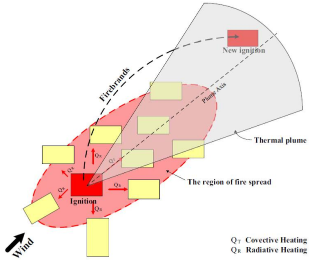
Earthquake



Nonlinear time-history analysis



Fire



Thermal plume and radiation-based fire spread simulation

Wind + …

Continuity: $\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$

X – Momentum: $\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial p}{\partial x}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}\right]$

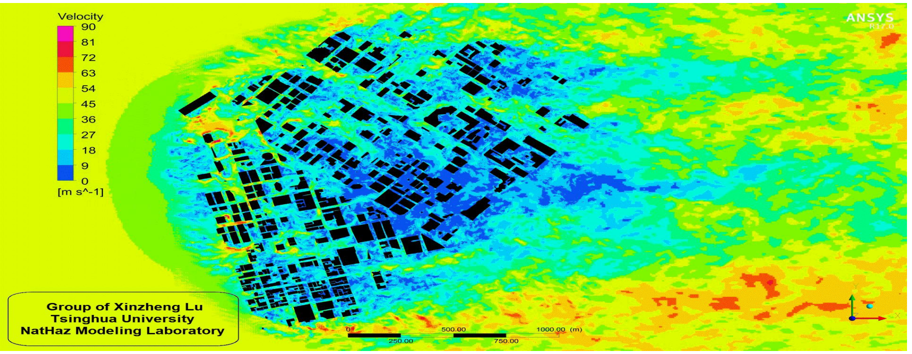
Y – Momentum: $\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=-\frac{\partial p}{\partial y}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}\right]$

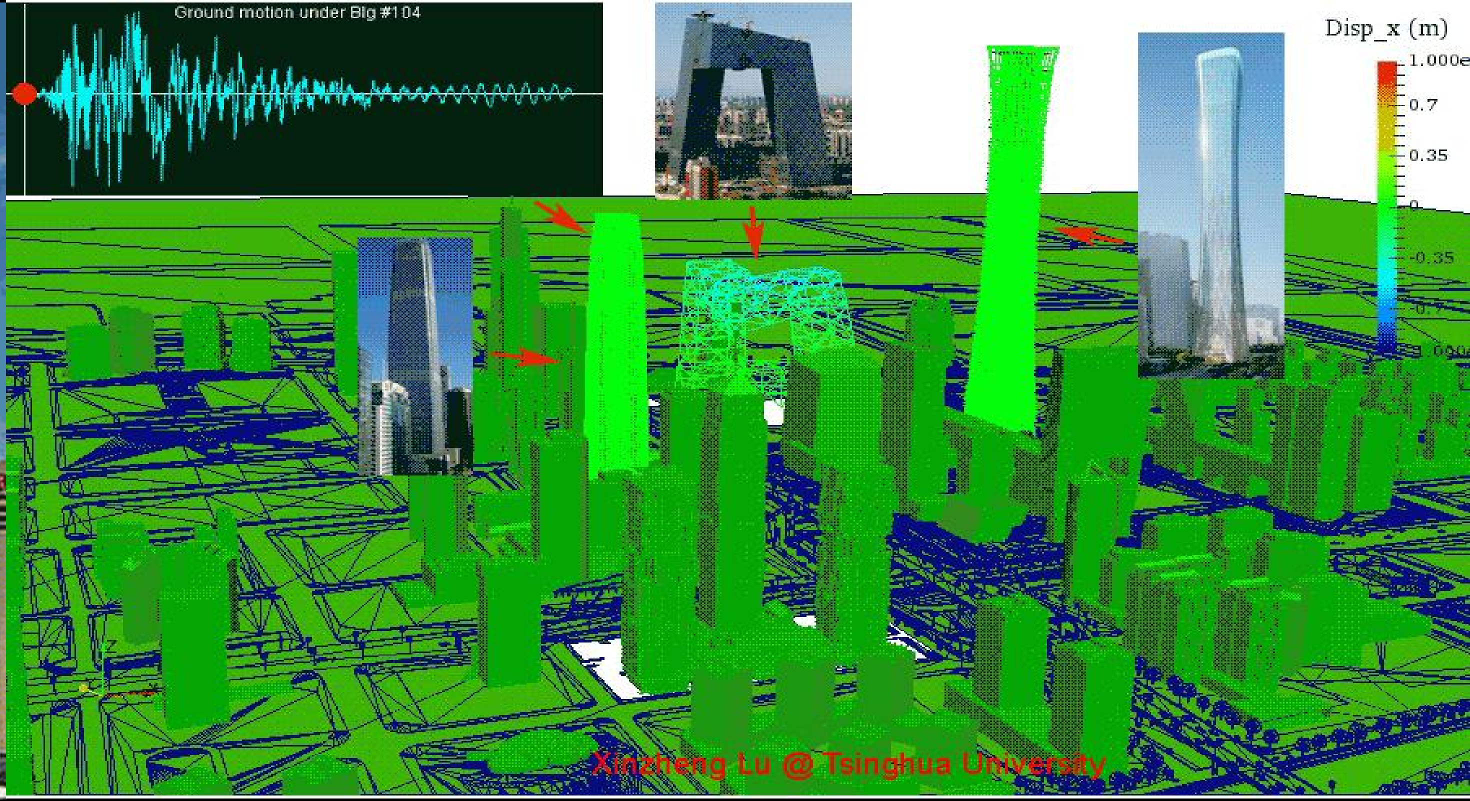
Z – Momentum $\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}\right]$

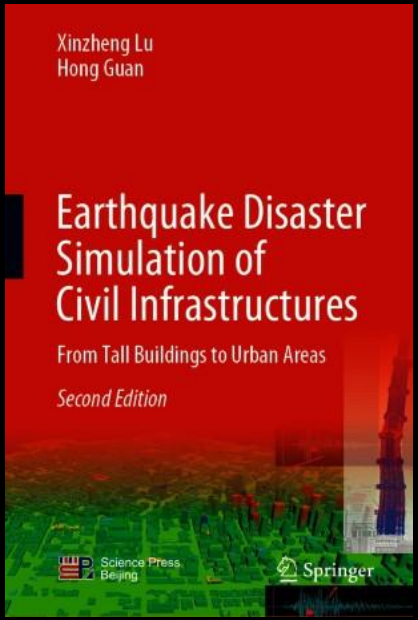
Energy:

$$\frac{\partial(E_T)}{\partial t}+\frac{\partial(uE_T)}{\partial x}+\frac{\partial(vE_T)}{\partial y}+\frac{\partial(wE_T)}{\partial z}=-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}-\frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right]$$
$$+\frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\tau_{xx}+v\tau_{xy}+w\tau_{xz})+\frac{\partial}{\partial y}(u\tau_{xy}+v\tau_{yy}+w\tau_{yz})+\frac{\partial}{\partial z}(u\tau_{xz}+v\tau_{yz}+w\tau_{zz})\right]$$

Large eddy simulation







Thank you for your attention !

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luxz@tsinghua.edu.cn