GPU-based high-performance computing for urban seismic damage prediction and visualization

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Outlines

- Introduction
- Program Framework
- Performance Benchmark
- Case Study
- Realistic Visualization
- Conclusions
Introduction

- China is subjected to most serious earthquake disaster threats in the world
- Earthquake occurs in cities will cause tremendous casualties and damage
- Scientific prediction of urban seismic damage is an important task
Introduction

- Methods for urban seismic damage simulation
  - Based on probability matrices
    - ATC-13
  - Based on capacity curve and response spectrum
    - HAZUS, AEBM

Problems:
- SDOF model
- Pushover analysis
- Demand Spectra
- ....
Introduction

“Nonlinear Time History Analysis of a City!”

Single structure
- Detailed structural information
- One building

Urban region
- Limited structural information
- Hundreds of thousands of buildings
Introduction

- University of Tokyo
- Integrated Earthquake Simulation

- Supercomputer with traditional **CPU** platform
  - Expensive 🚫
  - Complex 🚫
  - High maintenance costs 🚫
Introduction

- GPU (Graphic Processing Unit)

Comparison between the CPU and the GPU:

- **CPU**: 2~8 cores
- **GPU**: hundreds/thousands of cores
GPU-powered THA of Single Bld.

- Fiber beam element + Multi-layer shell element

Collapse simulation of Z15 in Beijing (H=550m)

Collapse simulation of Shanghai Tower (H=630m)

Collapse simulation of reinforced concrete high-rise building induced by extreme earthquakes, *Earthquake Engineering & Structural Dynamics*, 2013, 42(5)

Collapse simulation of a super high-rise building subjected to extremely strong earthquakes. *Science China Technological Sciences*, 2011, 54(10)
GPU-powered THA of Single Bld.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Hardware</th>
<th>Price</th>
<th>Solver</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>Intel Core i7-3970X 3.5GHz (Fastest CPU in the market)</td>
<td>US$2406</td>
<td>SparseSYM of OpenSees</td>
</tr>
<tr>
<td>GPU</td>
<td>Intel Core i7-4770X 3.4GHz &amp; NVIDIA GeForce GTX Titan</td>
<td>US$2307</td>
<td>CuSPSolver of OpenSees</td>
</tr>
</tbody>
</table>

14.87x faster!
The advantages for using GPU

<table>
<thead>
<tr>
<th>Seismic computing for normal buildings</th>
<th>Computing features of GPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple model, few degree-of freedom in a single building</td>
<td>Relatively weak performance of a single core</td>
</tr>
<tr>
<td>No interaction between buildings</td>
<td>Fewer data exchange</td>
</tr>
<tr>
<td>A huge number of buildings</td>
<td>Suitable for parallel computing</td>
</tr>
</tbody>
</table>

Lower cost  Higher performance

A coarse-grained parallel approach for seismic damage simulations of urban areas based on refined models and GPU/CPU cooperative computing, *Advances in Engineering Software*, 2014
A coarse-grained parallel approach for seismic damage simulations of urban areas based on refined models and GPU/CPU cooperative computing, *Advances in Engineering Software*, 2014
Building Models

- **Computational Model**
  - Multi-story concentrated-mass shear (MCS) model
    - Moderate workload
    - Consider higher-order vibration modes & velocity pulses
    - Damage locations on different stories can be obtained

- Suitable for GPU computing

A coarse-grained parallel approach for seismic damage simulations of urban areas based on refined models and GPU/CPU cooperative computing, *Advances in Engineering Software*, 2014
Building Models

- Inter-story hysteretic model
  - Backbone curve
    - Trilinear, 5 parameters

- Hysteretic model
  - Modified-Clough
  - Bilinear elasto-plastic
  - Pinching

A coarse-grained parallel approach for seismic damage simulations of urban areas based on refined models and GPU/CPU cooperative computing, *Advances in Engineering Software*, 2014
Building Performance Database

- For Regular Buildings
  - Based on the HAZUS performance database

- Parameter Set Selection
  - According to building macro-parameters
    - Structural types, Numbers of stories, Construction Period
  - 19 building types proposed in HAZUS are adopted

HAZUS Parameters \(\rightarrow\) convert \(\longrightarrow\) MCS model Parameters

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A coarse-grained parallel approach for seismic damage simulations of urban areas based on refined models and GPU/CPU cooperative computing, *Advances in Engineering Software*, 2014
For Special Buildings:

- Refined Numerical (RN) Model
- Objective Special Building
- Multi-story Concentrated-mass Shear (MCS) Model

Nonlinear Cyclic Pushover Analysis Normalized by the weight of one story

Nonlinear Cyclic Pushover Curve of RN model (Each Story)

Adjust the Parameters

Coincide or Not

Yes

No

Parameters of inter-story backbone curve and hysteretic model

Nonlinear Cyclic Pushover Curve of MCS model (Each story)
Building Performance Database

- Validation (six-story RC frame)

Refined FE model

Inter-story hysteretic model

Top displacement

Inter-story drift
Parallel Computing Method

- Pre-analysis Module
- Seismic Analysis Module
- Post-analysis Module

**Input Data for nonlinear THA**

**Copy Data to Graphic Memory**

**Assign Tasks for GPU**

**THA for Building #1**
**THA for Building #2**
**THA for Building #3**

**CPU**

**GPU**

**THA for Each Building**

**Copy Data to Host Memory**

**Output Damage & Response Data**
Performance Benchmark

- CPU/GPU cooperative vs. CPU only
  - **1,024 buildings**, numbers of stories and structural types are random generated
  - Earthquake record: El Centro, 40 s, PGA: 200 cm/s²
  - Time of data input and output is not included

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<tr>
<td>CPU</td>
<td>Intel Core i3 530 @2.93GHz &amp; DDR3 4G 1333MHz.</td>
<td>Microsoft Visual C++ 2008 SP1</td>
</tr>
<tr>
<td>GPU/CPU cooperative</td>
<td>Intel Celeron E3200 @ 2.4GHz &amp; NVIDIA GeForce GTX 460 1GB.</td>
<td>Microsoft Visual C++ 2008 SP1 &amp; CUDA 4.2</td>
</tr>
</tbody>
</table>

**The two platforms have similar prices**
Performance Benchmark

- Weak-scaling benchmarks for the two platforms
- **39x** speedup when computing 1024 buildings

A coarse-grained parallel approach for seismic damage simulations of urban areas based on refined models and GPU/CPU cooperative computing, *Advances in Engineering Software*, 2014
Case Study

- A medium-sized urban area in China
- 4,225 buildings
A coarse-grained parallel approach for seismic damage simulations of urban areas based on refined models and GPU/CPU cooperative computing, *Advances in Engineering Software*, 2014.

Case Study

- **Global view**
  - Damage on different stories

**Desktop Computer**

- 4,255 buildings
- 40 s time-history analysis
- Accomplished in 216 s

Damage state:

- None
- Slight
- Moderate
- Extensive
- Complete
Case Study

- Local view
  - Damage on different stories

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Case Study

- Local view
  - Peak acceleration on different stories
Case Study

MCS Model

SDOF Model

Far-field

Near-field without pulses

Near-field with pulses

MCS model: velocity pulses can be considered
Visualization problem

- Realistic visualization
- Rescue and transportation planning

- MCS model cannot simulate process of building collapse.

MCS model
(Criterion of collapse)

Real earthquake disaster
(Include building collapse)
Physics Engine Solutions

- Physics engine
  - A computer program for real-time dynamic calculation, good at multi-body dynamics.
  - Widely used in computer graphics, video games and film.

Example of physics engine

Seismic damage simulation in urban areas based on a high-fidelity structural model and a physics engine, *Natural Hazards*, 2014
Collapse simulation

- Integrate MCS model and physics engine

The process of collapse simulation in physics engine

Seismic damage simulation in urban areas based on a high-fidelity structural model and a physics engine, *Natural Hazards*, 2014
Collapse simulation

High-efficient collapse simulation.
Application for Tsinghua Campus

The campus of Tsinghua University
Conclusions

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With Texture  Disp. Contour  Damage State

Fast  Cheap  High-fidelity  Realistic
Nonlinear time history analysis: from mega-structures to cities?

Thank you for your attention!