Virtual Digital City and Urban Seismic Resilience

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Outline

1 Background
2 Digital city & earthquake scenario
3 Verification of disaster simulation
4 Typical application
5 Summary
1 Research background

- Mw7.8 Turkey earthquake on February 6, 2023
  - More than 50000 people killed and economic losses exceeded 100 billion dollars
1 Research background

The number, scale and population density of cities in China

Modern civilization and complex

Rapid development of urban scale

Proportion of megacity is the largest

Rapid development of urbanization resulted in dense infrastructures, large population, and concentration of wealth
Carrying 40% of the population with a land area of 3%
Creating 65% of GDP and 90% of total imports and exports

In the past 40 years, large cities in east of China haven’t experienced any major earthquakes, thus lack of related knowledge of emergency responses.
1 Research background


Huge earthquake
- Strong motion intensity
- Wide spatial distribution
- Significant dynamic characteristics
- Strong randomness

Huge Urban systems
- Dense population
- Intensive and diverse infrastructures
- Buildings at different ages
- Different anti-disaster ability

Huge EQ disasters
- Massive casualties
- Extensive damages of infrastructures and engineering systems
- Urban/regional functional loss
2 Digital city & earthquake scenario

- Digital and physical hybrid twins

- **Sensing**: Geographic information, monitoring network, remote sensing, Internet of things, big data
- **Simulation**: Online simulation, high performance computing, visualization, AI
- **Transmission**: High-speed networks (e.g. 5G technology)
2 Digital city & earthquake scenario

Scenario construction of earthquake disaster

- Seismic fault information and modeling
- Propagation path and wave field analysis
- Nonlinear engineering site effects
- Nonlinear response of engineering structures
- Engineering disasters and consequences

Uncertainty

- Different earthquake scenarios and consequences
- Different earthquake prevention strategies and effects
- Optimized earthquake prevention strategies and suggestions

Nonlinearity
## 1 Digital city: key data acquisition

<table>
<thead>
<tr>
<th>Category</th>
<th>Data content</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building architectural drawing and structure sketch + distribution data</strong></td>
<td><strong>Key attributes:</strong> building outline coordinates, building height (number of floors), building name and address, construction age, structural type, usage and function (residential, commercial, lifeline buildings, etc.), seismic fortification, geological conditions, underground space Information, land planning data, related electronic maps, typical building drawings</td>
</tr>
<tr>
<td><strong>Traffic facilities planar or three-dimensional map + road network distribution data</strong></td>
<td><strong>Key attributes:</strong> name, coordinates, road grade, road width (number of lanes), bridge and tunnel information, main structure type, material, geological conditions, underground space information</td>
</tr>
<tr>
<td><strong>Dynamic monitoring data</strong></td>
<td><strong>Key attributes:</strong> population distribution + thermo-dynamic data, traffic flow + traffic smoothness data, <strong>site and structural strong motion array records</strong></td>
</tr>
<tr>
<td><strong>Other lifeline facility distribution maps + distribution data</strong></td>
<td><strong>Key attributes:</strong> category (water supply, gas, etc.), pipe diameter, grade, material, buried depth, management department, geological conditions, secondary disaster sources</td>
</tr>
</tbody>
</table>

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2 Digital city & earthquake scenario
2 Digital city & earthquake scenario

- **Benchmark city model:**
  - Central urban area: 7,500 hectare
  - 5 city zones and 14 urban planning units
  - Population: 690,449
  - 337 residential units (Rescue demand point)
2 Digital city & earthquake scenario

- Benchmark city model: Structure types, number, height of buildings
  - Number of buildings: 9773

Distribution of buildings in central old city area

Distribution of buildings in the city
 Benchmark city model: Transportation system

- Number of roads: 1133
- Total length of roads: 485.7km
- Road width, design travel speed

<table>
<thead>
<tr>
<th>Road hierarchy</th>
<th>Travel speed (km/h)</th>
<th>Road length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-speed road</td>
<td>70</td>
<td>46684</td>
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<tr>
<td>Arterial road</td>
<td>60</td>
<td>149518</td>
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<tr>
<td>Secondary road</td>
<td>50</td>
<td>252209</td>
</tr>
<tr>
<td>Branch road</td>
<td>20</td>
<td>37263</td>
</tr>
</tbody>
</table>

2 Digital city & earthquake scenario
2 Digital city & earthquake scenario

- Benchmark city model

- Water distribution networks
  - Number of pipe segments: 323
  - Total length of pipes: 255km
  - Diameter, length, and material

- Power distribution networks
  - Number of 110kV substations: 14
  - Number of 220kV substations: 4
  - Capacity information
2 Digital city & earthquake scenario

➢ Benchmark city model

□ Drainage distribution networks
  • Number of pipe segments: 323
  • Total length of pipes: 255km
  • Diameter, length, and material

□ Natural gas distribution network
  • Total length of pipes: 323km
  • Diameter, length
2 Digital city & earthquake scenario

➢ Benchmark city model

☐ Hospital system

• 4 Level 2 and 4 Level 3 hospitals

<table>
<thead>
<tr>
<th>Hospital name</th>
<th>Hospital level</th>
<th>Stories</th>
<th>Patient beds</th>
<th>Medical staff</th>
<th>Clinical departments</th>
<th>Medical laboratories</th>
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</thead>
<tbody>
<tr>
<td>H-N-1</td>
<td>2</td>
<td>6</td>
<td>550</td>
<td>600</td>
<td>33</td>
<td>7</td>
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<tr>
<td>H-C-1</td>
<td>3</td>
<td>6</td>
<td>511</td>
<td>654</td>
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<td>10</td>
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<td>1161</td>
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<td>7</td>
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<tr>
<td>H-E-1</td>
<td>2</td>
<td>5</td>
<td>150</td>
<td>200</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>H-W-1</td>
<td>2</td>
<td>5</td>
<td>80</td>
<td>80</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>H-W-2</td>
<td>2</td>
<td>5</td>
<td>218</td>
<td>200</td>
<td>23</td>
<td>7</td>
</tr>
<tr>
<td>H-W-3</td>
<td>3</td>
<td>10</td>
<td>900</td>
<td>1000</td>
<td>24</td>
<td>7</td>
</tr>
<tr>
<td>H-S-1</td>
<td>3</td>
<td>10</td>
<td>1000</td>
<td>1100</td>
<td>28</td>
<td>8</td>
</tr>
</tbody>
</table>
2 Seismic reliability analysis of infrastructure networks

- Seismic resilience of water supply networks (WSN)

- **Step 1**: Water supply network
- **Step 2**: Seismic intensity estimation
- **Step 3**: Damage scenario generation
- **Step 4**: Hydraulic analysis
- **Step 5**: Functionality assessment
- **Step 6**: Resilience assessment
- **Step 7**: Results interpretation

Diagram:

1. Damaged WSN
2. Determine the number of damage to be repaired
3. Functionality improvement if one damage is repaired
4. Repair the damage that improves the functionality most
5. All damage repaired?
6. Yes
7. Calculate system recovery curve
   - No
   - Repair the damage that improves the functionality most
2 Digital city & earthquake scenario

2 Seismic reliability analysis of infrastructure networks

Seismic resilience of water supply networks (WSN)

Functionality

Pipe damage

Simulation model

Functionality restoration (mean/median)
Resilience assessment of urban telecommunication systems

- **Random sampling**: post-earthquake damage of components (building, equipment, towers,)
- **Fault tree analysis**: basic element (Switching center, convergence room, base station)
- **Network Connectivity Analysis**
- **Identifying stations that remain working normally after earthquakes**
- **The functionality level of the communication system:**

\[
F = \frac{N_{Avl}}{N_{Tot}}
\]

Design intensity: VII
1 Switching center
12 Convergence station
115 Basic Transceiver Station
25 Main Trunk Lines
180 Branch Lines

Functionality assessment under different intensities
2 Digital city & earthquake scenario

3 Urban Earthquake Disaster Simulator (YouSimulator)

- GIS data
- Monitoring data
- Ground motions

Automatic modeling
- Model updating

Building info.
- Structural models

3D Visualization

Time history responses of the floors of each building

Response computing

Results Analyses
- Story drift, Damage distribution
- Demand of shelters, Losses
- Recovery information

A code based on C++/Fortran (YouSimulator)
3 Urban Earthquake Disaster Simulator (YouSimulator)

GIS data
Building height or number of stories
Type of structure
Construction time

3D geometry info.

Floor area
Story stiffness
Story strength

Mechanical behavior of each story
Set parameters for each spring

Multi-shear-spring model

Non-uniform ground motion input for time history analyses

2 Digital city & earthquake scenario

 Urban Earthquake Disaster Simulator (YouSimulator)
2 Digital city & earthquake scenario

4 Online real-time simulation based on monitoring data

- System identification
- Cloud-based health monitoring system
- Data-driven online simulation system
- Upload
- Real-time ground motion
- Rapid damage evaluation of the nearby buildings

Collaborator: Beijing Earthquake Agency
3 Verification of disaster simulation

- Verification with earthquake disaster data of Christchurch under a series of earthquakes in New Zealand (2010-2011)

Distribution of the severely damaged or collapsed buildings generally agrees with distribution of demolished buildings.

- Simulation
  - Severe/collapsed 16.1%
  - Intact/slight/moderate

- Field survey (2013)
  - Demolished 26.2%
  - Undemolished
3 Verification of disaster simulation

- Verification by field survey of 2014 Ludian Earthquake

Over 60% buildings present correct damage states at the first round of simulation
3 Verification of disaster simulation

- Verification by field survey of 2021 Yangbi earthquake

The seismic damages were well reproduced by YouSimulator.
3 Verification of disaster simulation

- Verification by field survey of 2022 Luding Earthquake

 Obtained from UAV image
 (Global damage index = 0.63)

Simulation (Global damage index = 0.63)
3 Verification of disaster simulation

➢ Simulation and verification on the spread of the secondary fire: Kobe earthquake (1995)
4 Typical application

- Earthquake disaster simulation (Chongli district)

Subjected to seismic intensity 9
4 Typical application

- Earthquake disaster simulation (Tangshan)
4 Typical application

- Demand of shelters for each community

A new town in the southwest of China with over 5000 buildings
4 Typical application

- Path plan for emergency rescue
  - Building damage
  - Simulation of falling debris
  - States of road network
  - Simulation of transportation
  - Functionality loss of road network
5 Summary

• The digital-physical hybrid twin technology is one of the important approaches to address the challenges of disaster management in large cities;
• The proposed digital twin and disaster scenario construction technology exhibit advanced features in model generation, computational efficiency, and accuracy;
• This technology can be utilized in urban disaster prevention planning, urban renewal, disaster emergency management, and so on.
• Further research is still needed on the completeness of urban data and the interdependence among engineering systems.
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Thanks for your attention!

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