Integrating Performance-Based Engineering and Urban Simulation to Model Post-Earthquake Housing Recovery

Henry Burton Ph.D., S.E. (Assistant Professor)
Hua Kang (PhD Candidate)

Department of Civil and Environmental Engineering
University of California, Los Angeles

PEER Annual Meeting

January 18, 2017
Practical Applications of Post-Earthquake Recovery Models:

Explore “What-If” Recovery Scenarios

Time (days)

Normalized Housing Capacity

- “Occasional” Event
- “Rare” Event
- “Rare” Event Enhanced Building Performance
- Increased Insurance Penetration
- Existing Inventory
- Existing Inventory with Increased Insurance Penetration

Normalized Housing Capacity

400
700
1000

quake
Practical Applications of Post-Earthquake Recovery Models: Develop “Resilience-Based” Infrastructure Performance Targets

Community resilience goal for “rare” event
- Overall community functionality restored to approximate pre-event level within 6 months

Residential Neighborhood
- 95% livable permanent housing within 90 days

Major Port
- 95% of pre-event container movement capacity restored within 6 months

Major Bridge
- 90% of pre-event level of vehicular movement restored within 30 days

Healthcare System
- Pre-event emergency response time restored within 7 days

Sea wall
- Earthquake damage repaired within 7 days

Commercial Center
- Pre-event business activity restored within 6 months

Figure adapted from Madeleine Flint (2017)
Post-Earthquake Recovery Modeling Framework: 
*Multi-Scale Process-Based Model*

Building Damage Evaluators → Local Insurance Market → Emergency Management

State and/or Federal Resources:
- Recovery Financing
- Disaster Support

Local Resources:
- Construction Labor Force
- Building Department
- Lifelines

Building and Household Recovery Processes:
- Assess Building Damage
- Access Financing
- Acquire Permits
- Perform Repairs

Endogenous/Exogenous Impediments

Unsafe to Occupy

Performance Limit State
Structural Response & Damage Analysis

Earthquake Shaking Intensity
Hazard Characterization

Building Functioning State
Decision Analysis

Community Recovery Trajectories
Urban Simulation

Sell w/o Repairing
Building Performance Limit States that Inform Post-Earthquake Recovery and Functionality

Building Performance Limit States:

- **collapse LS\(_5\)**
  - demolish and rebuild
- **irreparable damage LS\(_4\)**
  - demolish and rebuild
- **building unsafe LS\(_3\)**
  - vacate during repairs
  - occupy during repairs
  - occupy after inspection
- **repairable damage**
  - safe to occupy
  - functionality maintained LS\(_1\)
- **no collapse**
  - inspection triggered
  - repairable damage
  - inspection not triggered LS\(_0\)
  - continued occupancy

Recovery Activities:

- **no collapse**
- **irreparable damage**
- **building unsafe**
- **repairable damage**
- **inspection triggered**
- **inspection not triggered LS\(_0\)**

Mapping Fragility Function Parameters from “Loss-Based” to “Recovery-Based” Limit States

\[ P(RBLS = rbls_i \mid S_d) = \sum_{j=1}^{n_{lbds}} P(RBLS = rbls_i \mid LBDS = lbd_{j}) \cdot P(LBDS = lbd_{j} \mid S_d) \]

\( RBLS \): Recovery-based limit state  \( LBDS \): Loss-based damage state  \( S_d \): Spectral displacement

<table>
<thead>
<tr>
<th>Loss-Based Damage States</th>
<th>( P(RBLS = rbls_i \mid LBDS = lbd_{j}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS1 Fully Functional</td>
<td>\begin{tabular}{c</td>
</tr>
<tr>
<td>LS2 Loss of Functionality</td>
<td>\begin{tabular}{c</td>
</tr>
<tr>
<td>LS3 Unsafe to Occupy</td>
<td>\begin{tabular}{c</td>
</tr>
<tr>
<td>LS4 Damaged Beyond Repair</td>
<td>\begin{tabular}{c</td>
</tr>
<tr>
<td>LS5 Collapse</td>
<td>\begin{tabular}{c</td>
</tr>
</tbody>
</table>

Graphs showing the probability of exceeding limit states for different spectral displacements.
# Modeling Household Decision-Making

![Decision Tree Diagram](image)

### Recovery-Based Limit State, $[LS_i]$

- **Repair/replace + sell, $[A_1|LS_i]$**
- **Repair/replace + reoccupy, $[A_2|LS_i]$**
- **Abandon, $[A_3|LS_i]$**
- **Sell without repairing, $[A_4|LS_i]$**

<table>
<thead>
<tr>
<th>No.</th>
<th>Neighborhood Vacancy</th>
<th>Physical Damage to Residence</th>
<th>Loss of Utilities</th>
<th>Building Access</th>
<th>You have earthquake insurance</th>
<th>You do NOT have earthquake insurance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Reoccupy, Sell w/ Repair, Sell w/o Repair</td>
<td>Reoccupy, Sell w/ Repair, Sell w/o Repair</td>
</tr>
<tr>
<td>1</td>
<td>Almost Half</td>
<td>None</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>None</td>
<td>None</td>
<td>24hrs</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Almost Half</td>
<td>None</td>
<td>24hrs</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>None</td>
<td>Minor or None</td>
<td>2 weeks</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Almost Half</td>
<td>Minor or None</td>
<td>2 weeks</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Almost Half</td>
<td>Moderate or Lower</td>
<td>3 months</td>
<td>&lt;3 months</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Almost All</td>
<td>Moderate or Lower</td>
<td>3 months</td>
<td>&lt;3 months</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>None</td>
<td>Minor</td>
<td>&lt;2 weeks</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Building-Level Recovery: Empirically-Based Stochastic Process Model

Recovery State, $Y(t)$

Stochastic recovery function

Discrete recovery states

$\text{OccFull}$: Occupiable and fully functional

$\text{OccLoss}$: Occupiable with loss of functionality

$\text{NOcc}$: Not occupiable

$$P(t < T < t + \Delta \mid T > t) = 1 - \frac{e^{-\lambda(t+\Delta)}}{e^{-\lambda t}}$$
Building-Level Recovery: *Empirically-Based Stochastic Process Model*

![Diagram showing stochastic recovery function]

\[
P(t < T < t + \Delta | T > t) = 1 - \frac{e^{-\lambda(t+\Delta)}}{e^{-\lambda t}}
\]
Building-Level Recovery: Simulation-Based Stochastic Process Model

Simulate Process Dynamics with Explicit Consideration of Resources, Interactions and Impeding Factors
Simulating Building Damage Evaluation Dynamics

Neighborhood 1 - > Team A

Neighborhood 2 - > Team B

Neighborhood 3 - > Team C
Simulating Building Repair/Reconstruction Dynamics

“Dealing card” algorithm for sequencing and allocating building repairs to contractors

<table>
<thead>
<tr>
<th>Contractors</th>
<th>Number of Teams</th>
<th>Work-Hours Per Day Per Team</th>
<th>Capacity</th>
<th>Number of Assigned Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contractor A</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>500</td>
</tr>
<tr>
<td>Contractor B</td>
<td>3</td>
<td>10</td>
<td>3</td>
<td>300</td>
</tr>
<tr>
<td>Contractor C</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>200</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>1000</td>
</tr>
</tbody>
</table>

Contractor A

Contractor B

Contractor C
Integrating Stochastic Recovery Process and Household Decision Model: *Probabilistic Decision Path Model*

- Occupied and fully functional, (OccFull)
- Occupied with loss of functionality, (OccLoss)
- Unsafe and unoccupied, (UnOcc)

Possible Paths to Recovery

Decision Path 1
Decision Path 2
Decision Path 3
Decision Path 4

Functioning State

Time

$T_{\text{UnOcc},1}$ $T_{\text{OccLoss},1}$ $T_{\text{OccFull},1}$
Probabilistic Community-Level Housing Recovery Trajectories

Probabilistic Recovery Function

CDF of Recovery Level at 200 days
Probabilistic Community-Level Housing Recovery Trajectories

Probabilistic Recovery Function

CDF of Time to Recover to 90% Pre-Earthquake Capacity
Validation Case Study: 2014 South Napa Earthquake

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Number of Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location, ATC-20 Tag, and damage description</td>
<td>1470</td>
</tr>
<tr>
<td>Sociodemographic (census) and building characteristic data</td>
<td>1470</td>
</tr>
<tr>
<td>Building permit issue and completion date</td>
<td>456</td>
</tr>
</tbody>
</table>

Observed Damage (red- and yellow-tagged buildings)
Validation Study: 1) Generate observed recovery curve for 456 damaged buildings based on time-to-permit and repair time.
Validation Study: 2) Assign HAZUS-Type damage states to all 1470 damaged buildings

<table>
<thead>
<tr>
<th>Building No.</th>
<th>Field Inspection Damage Description</th>
<th>ATC-20 Tag</th>
<th>HAZUS Damage State Description</th>
<th>HAZUS Damage State</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Top of brick chimney fell down</td>
<td>Yellow</td>
<td>Toppling of tall masonry chimneys</td>
<td>moderate</td>
</tr>
<tr>
<td>2</td>
<td>Racking, cracking and separation of cripple walls; floors uneven/waving; unstable house</td>
<td>Red</td>
<td>Large foundation cracks, some structures may slip and fall off the foundations, and may collapse</td>
<td>complete</td>
</tr>
<tr>
<td>3</td>
<td>Minor cracks in chimney; no structural issues; suggest inspect chimney for integrity</td>
<td>Yellow</td>
<td>Small cracks in masonry chimney</td>
<td>slight</td>
</tr>
<tr>
<td>4</td>
<td>Numerous wall cracks throughout living room kitchen and dining room; chimney collapsed</td>
<td>Yellow</td>
<td>Large diagonal cracks across wall panels or plywood joints; toppling of most brick chimneys</td>
<td>extensive</td>
</tr>
<tr>
<td>5</td>
<td>Collapse imminent</td>
<td>Red</td>
<td>Structural collapsed occurred or is imminent due to failure of cripple wall or the lateral load resisting system</td>
<td>complete</td>
</tr>
</tbody>
</table>
Validation Study: 3) Generate empirically-based “blind” recovery trajectory using HAZUS recovery times
Validation Study: 4) Generate *empirically-driven* recovery trajectory using mean time-to-permit and repair time dataset.

![Graph showing normalized functionality over time](image)

- **“Updated” Empirically-Based Recovery Model**
- **Observed Recovery**
5) Develop statistical model for estimating time-to-permit and repair time based on damage, building attributes (e.g. building age, property value) and socio-demographic data (e.g. mean household income, percentage of owner-occupied buildings).
Validation Study: 6) Generate empirically-based recovery trajectory for 1470 buildings using generalized model from step 5
The End

Presenter Contact Information
Henry V. Burton, PhD., S.E.
hvburton@ucla.edu
www.henryburtonjr.com