Liquefaction Evaluations and Mapping

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University of Utah Asia Campus
Background

- B.S. Degree (1983) Brigham Young University
- Ph.D. Degree (1988 - 1992) Brigham Young University
  - Dr. T. Leslie Youd (Advisor)
  - Empirical Analysis of Liquefaction-Induced Lateral Spread
  - Seismic and Liquefaction Evaluations of Nuclear Facilities
  - Liquefaction Evaluations for I-15 Interstate Reconstruction for 2002 Winter Olympic Games – Salt Lake City, Utah
- Research Engineer – Utah Department of Transportation (1999)
- University of Utah (2000 – present)
Topics

- Liquefaction Effects
- Liquefaction Evaluations
- Liquefaction Research
- Liquefaction Maps
- Liquefaction Hazard Assessment
- Pipeline Protection
- Seismic Buffers
- Unreinforced Masonry (URM) Retrofitting
Liquefaction Effects

Sand Blow or Sand Volcano
Liquefaction Effects

Ground Oscillation

Marina District, San Francisco, 1989 Loma Prieta Earthquake
Liquefaction Effects

Ground Settlement

2011 Tohoku, Japan Earthquake
Liquefaction Effects

1964 Niigata, Japan Earthquake

Bearing Capacity Failure

1964 Niigata, Japan Earthquake
Liquefaction Effects

Lateral Spread

- Power poles are pulled over by their wires as they can’t be supported in the liquefied ground. Underground cables are pulled apart.
- Lateral Spreading: River banks move toward each other. Cracks open along the banks. Cracking can extend back into properties, damaging houses.
- Fine sand and silt liquefies, and water pressure increases.

1964 Niigata, Japan Earthquake

Port of Kobe, 1995 Kobe, Japan Earthquake

2011 Tohoku, Japan
Liquefaction Effects

Valdez, 1964
Alaska
Earthquake

Flow Failure

Palu, 2018 Indonesian
Earthquake
Topics

- Liquefaction Effects
- **Liquefaction Evaluations**
- Liquefaction Research
- Liquefaction Maps
- Liquefaction Hazard Assessment
- Pipeline Protection
- Seismic Buffers
- Unreinforced Masonry (URM) Retrofitting
Liquefaction Evaluations

1. Three questions must be assessed when evaluating the liquefaction hazard of a given site.
   i) Is the soil potentially susceptible to liquefaction?
   ii) If potentially susceptible, will liquefaction be triggered by an earthquake event?
   iii) If liquefaction is triggered, what will be the consequences of liquefaction (i.e., what are the consequences and the potential magnitude of displacement?)
Liquefaction Evaluation Methods

Liquefaction Triggering Curves

CSR/CRR

Liquefied sites

Corrected SPT, CPT, or Vs

Liquefaction triggering curve

Non-Liquefied sites
Liquefaction Evaluations

- SPT method
- CPT method
- Vs method
SPT methods

Mud Rotary Drilling

Standard Penetration Test
CPT Methods

Cone Penetration Test
Vs Testing

Shear Wave Velocity, Vs, Test
SPT Liquefaction Curves

Seed, Idriss and Arango
SPT Liquefaction Curves

Seed, Idriss and Arango
SPT Liquefaction Curves

Idriss and Boulanger
Topics

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- Liquefaction Evaluations
- Liquefaction Research
- Liquefaction Maps
- Liquefaction Hazard Assessment
- Pipeline Protection
- Seismic Buffers
- Unreinforced Masonry (URM) Retrofitting
Liquefaction Research

Pacific Earthquake Engineering Research (PEER) – Development of Next Generation Liquefaction (NGL) Database for Liquefaction-Induced Lateral Spread

**Lateral Spread Research Team**

- University of Utah, Steven Bartlett (Lead)
- University of Washington, Steven Kramer
- Brigham Young University, Kevin Franke
- NOAA, Daniel Gillins (Consultant)

[https://peer.berkeley.edu/ngl](https://peer.berkeley.edu/ngl)
Goals of PEER NGL Project

1. **improve** the quality, transparency, and accessibility of **case history data** related to ground failure;
2. provide a **coordinated framework** for supporting studies to **augment case history data** for conditions important for applications but poorly represented in empirical databases;
3. provide an **open, collaborative process for model development** in which developer teams have access to common resources and share ideas and results during model development, so as to reduce the potential for mistakes and to mutually benefit from best practices.
Project Objectives

1. Develop **peer-reviewed and consistent methodology** for data documentation and archiving of lateral spread case histories.
2. Develop **quality assurance protocols** for assessing and documenting data quality.
3. Develop methods and/or protocols to **quantify uncertainties associated with the collected data**.
4. Populate the case history database with **well-documented examples of liquefaction-induced lateral spread**.
5. Review **screening criterion** used in evaluating lateral spread potential.
6. Disseminate **the database for general use** using web-based software
Types of Data in Database

- Seismological Factors
- Topographical Factors
- Geotechnical / Soil Factors
- Damage and Ground Displacement Data
Seismological Factors

<table>
<thead>
<tr>
<th>Earthquake Name and Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake Magnitude, Mw</td>
</tr>
<tr>
<td>Location</td>
</tr>
<tr>
<td>Source Distance Measures, Rrup, Rjb, etc.</td>
</tr>
<tr>
<td>Peak Ground Acceleration</td>
</tr>
<tr>
<td>Other measures of intensity (MMI, spectral accelerations, etc.)</td>
</tr>
<tr>
<td>Duration</td>
</tr>
<tr>
<td>Nearby accelerogram (if available)</td>
</tr>
</tbody>
</table>
Seismological Factors

Epicenters and Crustal Warping - 1964 Alaska Earthquake
Seismological Factors

Geological and Seismological Context of Seismicity in Christ Church, New Zealand
Seismological Factors

Earthquake Strong Motion Map

2011 Honshu Earthquake
Seismological Factors

1964 Niigata Japan Earthquake

Dynamic: Foundation failure by liquefaction after the 1964 Niigata Earthquake. (USGS)
Topographical Factors

20 Mile River - 1964
Alaska Earthquake
## Geotechnical / Soil Factors

<table>
<thead>
<tr>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological unit and type of sediments</td>
</tr>
<tr>
<td>Age of sediments</td>
</tr>
<tr>
<td>Depth to groundwater</td>
</tr>
<tr>
<td>Geological map (if available)</td>
</tr>
</tbody>
</table>
### TABLE 8-1

**SUSCEPTIBILITY OF SEDIMENTARY DEPOSITS TO LIQUEFACTION DURING STRONG SHAKING**

(After Youd and Perkins, 1978, Reprinted by Permission of ASCE)

<table>
<thead>
<tr>
<th>Type of Deposit</th>
<th>General Distribution of Cohesionless Sediments in Deposits</th>
<th>Likelihood that Cohesionless Sediments, When Saturated, Would Be Susceptible to Liquefaction (by Age of Deposit)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt;500 Year</td>
</tr>
<tr>
<td><strong>Continental Deposits</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River channel</td>
<td>Locally variable</td>
<td>Very high</td>
</tr>
<tr>
<td>Flood plain</td>
<td>Locally variable</td>
<td>High</td>
</tr>
<tr>
<td>Alluvial fan and plain</td>
<td>Widespread</td>
<td>Moderate</td>
</tr>
<tr>
<td>Marine terraces and plains</td>
<td>Widespread</td>
<td>Low</td>
</tr>
<tr>
<td>Delta and fan-delta</td>
<td>Widespread</td>
<td>High</td>
</tr>
<tr>
<td>Lacustrine and playa</td>
<td>Variable</td>
<td>High</td>
</tr>
<tr>
<td>Colluvium</td>
<td>Variable</td>
<td>High</td>
</tr>
<tr>
<td>Talus</td>
<td>Widespread</td>
<td>Low</td>
</tr>
<tr>
<td>Dunes</td>
<td>Widespread</td>
<td>High</td>
</tr>
<tr>
<td>Loess</td>
<td>Variable</td>
<td>High</td>
</tr>
<tr>
<td>Glacial till</td>
<td>Variable</td>
<td>Low</td>
</tr>
<tr>
<td>Tuff</td>
<td>Rare</td>
<td>Low</td>
</tr>
<tr>
<td>Tephra</td>
<td>Widespread</td>
<td>High</td>
</tr>
<tr>
<td>Residual soils</td>
<td>Rare</td>
<td>Low</td>
</tr>
<tr>
<td>Sebka</td>
<td>Locally variable</td>
<td>High</td>
</tr>
</tbody>
</table>
Geotechnical / Soil Factors

Seward Geologic Map - 1964
Alaska Earthquake
Geotechnical / Soil Factors

(a) Old Water Front circa 1600  (b) Old Water Front in 1911

Figure 7. Change of the Shinano River Course

1964 Niigata, Japan Earthquake
1983 Borah Peak Idaho Earthquake
Geotechnical / Soil Factors
Damage / Ground Displacement

LiDAR hillshade DEMs (illuminated from the NW) of three ~1.8 km long sections of the Greendale Fault – Darfield New Zealand Earthquake
Figure F1.1: Lateral spreading and free field liquefaction observations during the CES. The lateral spreading observations shown include recorded ground cracks and observations of lateral spreading on residential properties. Free field liquefaction observations shown are based on land damage observations on residential properties.
Damage / Ground Displacement

1964 Niigata, Japan Earthquake
Bridge Damage from Lateral Spread

- Jack-Knifed Bridge due to Compression
- Skewed Bridge due to Compression
- Differential Settlement and Compression

(McCulloch and Bonilla, 1970)
Relational Databases

- Currently in Microsoft Access; could be translated into other database management systems such as MySQL
- Compatible with Electronic Transfer of Geotechnical and Geoenvironmental Data (AGS4) formatting
- Displacement vectors, bore logs, and topology with their spatial coordinates in database
- Other data as flatfiles (or Binary Large Objects, BLOBs)
Topics

- Liquefaction Effects
- Liquefaction Evaluations
- Liquefaction Research
- Liquefaction Maps
- Liquefaction Hazard Assessment
- Pipeline Protection
- Seismic Buffers
- Unreinforced Masonry (URM) Retrofitting
Liquefaction Maps

- Liquefaction Mapping Program funded by the National Earthquake Hazard Program funded by the United States Geological Survey (USGS)
- Began in 2003 and continues till today
- Produce Several Liquefaction and Ground Displacement Maps for Utah
- Several Mapping Products have been developed
Types of Liquefaction Maps

- Liquefaction Susceptibility Maps
- Liquefaction Potential Maps
- Ground Failure Maps
Liquefaction Susceptibility Maps

- Liquefaction Susceptibility Maps
  - Show liquefaction hazard based on **susceptibility (soil natural resistance)**, but do not consider demand (size or amplitude of strong ground motion)
  - Usually based on surficial geologic maps with very little to no subsurface information
Types of Liquefaction Maps

- Liquefaction Susceptibility Maps
- Liquefaction Potential Maps
- Ground Failure Maps
Estimation of Liquefaction Potential

\[ P(L) = \sum P[L | A,M] \cdot P[A, M] \]

where:

- \( P(L) \) = annual probability of liquefaction
- \( P[L | A,M] \) = conditional probability of liquefaction given the peak ground acceleration and the earthquake magnitude,
- \( P[A, M] \) = joint probability density function of peak ground acceleration and earthquake magnitude.
Estimation of Liquefaction Potential

Estimates of peak ground acceleration (Wong et al., 2002)
Estimation of Liquefaction Potential

Geologic Map

Geotechnical Boreholes
Estimation of Liquefaction Potential

Groundwater Depth Map

Legend
Groundwater Depths (ft)
- 0 - 4 ft
- 4 - 8 ft
- 8 - 16 ft
- 16 - 32 ft
- 32 - 64 ft
- 64 - 100 ft

Projection:
UTM NAD 83 Zone 12 N
Recommended “Probabilistic” SPT-Based Liquefaction Triggering Correlation
(For $MW=7.5$ and $\sigma_v'=1.0$ atm)
(Seed et al. 2003)
Liquefaction Potential Map

- Liquefaction Potential Maps
- Combine liquefaction susceptibility (capacity) with seismic input (demand).
- Demand can be expressed as a deterministic scenario event or a probabilistic-based estimate obtained from a probabilistic seismic hazard analysis (PSHA)
Types of Liquefaction Maps

- Liquefaction Susceptibility Maps
- Liquefaction Potential Maps
- Ground Failure Maps
Estimation of Ground Displacement

\[ P(DH > x) = \sum P\left( \frac{DH}{L} > x \right) P[L | A, M, R] P[A, M, R] \]

where:

- \( P(DH>x) \) = The probability of lateral spread exceeding a threshold value (e.g., \( x = 0.1 \) m and 0.3 m)
- \( P[L | A,M,R] \) = the probability of liquefaction given an acceleration, magnitude, and source distance.
- \( P[A,M,R] \) = joint probability density function of peak ground acceleration, magnitude and source distance.
Estimation of Ground Displacement

Bartlett and Youd (1995); Youd, Hansen, Bartlett (2002); Gillins and Bartlett (2014).

\[ \log D_H = b_0 + b_{\text{off}} \alpha + b_1 M + b_2 \log R^* + b_3 R + b_4 \log W + b_5 \log S + b_6 \log T_{15} + b_7 \log (100 - F_{15}) + b_8 \log (D50_{15} + 0.1 \text{ mm}) \]

- Seismic Factors
  - \( M, R \)
- Topographic Factors
  - \( W, S \)
- Geotechnical Factors
  - \( T_{15}, F_{15}, D50_{15} \)

Free-face ratio: \( W \ (%) = \frac{H}{L} \times 100 \)
Estimation of Ground Displacement

Boreholes, Surficial Geology Map, Digital Elevation Model
Lateral Spread Ground Failure Map

- Ground Failure Maps
- Consider liquefaction potential
- Consider the amount of liquefaction displacement (e.g., lateral spread or ground settlement)
Maps 2500 and 500-year scenarios
Bridge Locations, Salt Lake County
Topics

- Liquefaction Effects
- Liquefaction Evaluations
- Liquefaction Research
- Liquefaction Maps
- Liquefaction Hazard Assessment
- Pipeline Protection
- Seismic Buffers
- Unreinforced Masonry (URM) Retrofitting
Bridge Fragility Curves

Figure 19: Polynomial fit fragility curves for continuous bridges with seat abutments (Brandenberg, Zhang, Kashighandi, Huo, & Zhao, 2011)
Vulnerable Bridges in Salt Lake Co.

FIGURE 2 Vulnerable Links Located in Salt Lake County, Utah.
Prioritize Critical Bridges for Repair
Topics

- Liquefaction Effects
- Liquefaction Evaluations
- Liquefaction Research
- Liquefaction Maps
- Liquefaction Hazard Assessment
- Pipeline Protection
- Seismic Buffers
- Unreinforced Masonry (URM) Retrofitting
Slot Trench Cover System at Fault Crossing

Crossing of Wasatch Fault Zone in with High-Pressure Gas Line
Salt Lake City, Utah, Questar Gas Corp.
Geofoam - Pipe Interaction
Geofoam Stress – Strain Curves

The graph shows the normalized vertical stress plotted against axial strain for different EPS densities: EPS 39, EPS 29, EPS 25, EPS 19, and EPS 15. The graph includes two allowable stress levels: one for dead load and another for dead + earthquake loads. The axial strain is given in percentage (%).
Geofoam Test Results - Cycling

Figure 2-18 Results of cyclic uniaxial tests on three samples at three different levels of cyclic deviatoric stresses under peak load with 15 number of cycles on EPS 25.

- $\sigma_{ds} = 72$ kPa
- $\Delta\sigma_{dc(0.5 \%)} = 27$ kPa
- $\Delta\sigma_{dc(0.75 \%)} = 36$ kPa
- $\Delta\sigma_{dc(1.0 \%)} = 43$ kPa
- $f = 1$ Hz

0.5% - 15 cycles - peak load
0.75% - 15 cycles - peak load
1.0% - 15 cycles - peak load
Sketch of Geofoam – Pipe Test Facility
Geofoam-Pipe Uplift Field Tests
Force-Displacement from Uplift Tests

![Graph showing force-displacement relationship with annotations on initiation of interface sliding and shear along trench walls, and compression of geofoam block prior to sliding and shear.]

- **Geofoam Cover**
- **Clay Cover**
Topics

- Liquefaction Effects
- Liquefaction Evaluations
- Liquefaction Research
- Liquefaction Maps
- Liquefaction Hazard Assessment
- Pipeline Protection
- **Seismic Buffers**
- Unreinforced Masonry (URM) Retrofitting
Seismic thrust greatly reduced due to low unit weight (mass) and compressibility of Geofoam.
Geofoam – Seismic Buffers

Federal Courthouse – Salt Lake City

IHC Hospital – Murray, Ut

Casino/Hotel – Reidoso, NM
Topics

- Liquefaction Effects
- Liquefaction Evaluations
- Liquefaction Research
- Liquefaction Maps
- Liquefaction Hazard Assessment
- Pipeline Protection
- Seismic Buffers
- Unreinforced Masonry (URM) Retrofitting
Unreinforced Masonry Collapse
Unreinforced Masonry Collapse

**Human Impact**

<table>
<thead>
<tr>
<th>Casualties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Life Threatening Injuries</td>
<td>7,400 - 9,300</td>
</tr>
<tr>
<td>Fatalities</td>
<td>2,000 - 2,500</td>
</tr>
</tbody>
</table>

**Building Damage**

<table>
<thead>
<tr>
<th>Damage Category</th>
<th>Number of Buildings Affected</th>
<th>Percent of 757,000 Total Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight</td>
<td>125,500</td>
<td>16.58%</td>
</tr>
<tr>
<td>Moderate</td>
<td>78,400</td>
<td>10.36%</td>
</tr>
<tr>
<td>Extensive</td>
<td>48,800</td>
<td>6.45%</td>
</tr>
<tr>
<td>Complete</td>
<td>55,400</td>
<td>7.32%</td>
</tr>
</tbody>
</table>

The scenario shows that 90,200 URM buildings—over 61 percent of the total number in the 12-county area—will be moderately damaged or totally destroyed following a magnitude 7.0 earthquake. Many

**Economic Impact**

<table>
<thead>
<tr>
<th>Estimated Short-Term Economic Loss</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Building-Related</td>
<td>$24.9 billion</td>
</tr>
<tr>
<td>Income</td>
<td>$6.9 billion</td>
</tr>
<tr>
<td>Lifeline-Related</td>
<td>$1.4 billion</td>
</tr>
<tr>
<td>Total</td>
<td>$33.2 billion</td>
</tr>
</tbody>
</table>
Structural Insulated Panels (SIPs)
SIP Retrofitting of Brick

- Oriented Strand Board (OSB) Sheeting
- Expanded Polystyrene (EPS) Insulation Core
- Bonding of OSB to Brick
- Anchors
- Brick
University of Utah Asia Campus
University of Utah Salt Lake Campus
For more information:

http://www.civil.utah.edu/~bartlett/pubs/