Linking Liquefaction Triggering to Damage Potential

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Acknowledgements

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Outline

- 2010-2011 Canterbury Earthquake Sequence
- Soils of Christchurch
- Evaluation of CPT-Based Liquefaction Evaluation Procedures
- Liquefaction Damage Indices
  - Liquefaction Potential Index (LPI)
  - Ishihara’s H$_1$-H$_2$ Chart
  - LPI$_{ISH}$
- Aging Effects
- Summary of Conclusions
- Work in Progress/Future Directions
2010-2011 Canterbury Earthquake Sequence
Poorly Defined Tectonics

Plate Boundaries:

- Divergent
- Convergent
- "Teeth" on Overriding Plate
- Transform
- Poorly Defined
2010-2011 Canterbury Earthquake Sequence

4 Sept 2010 $M_w$7.1, Darfield Earthquake

22 Feb 2011 $M_w$6.2, Christchurch Earthquake

23 Dec 2011 $M_w$6.0 Earthquake

13 June 2011 $M_w$6.0 Earthquake

Seismicity to 13th March, 2012
Statistics

- **Liquefaction Effects:**
  - Residential Properties: 60,000 affected
    - 20,000 severely affected
    - 8,000 abandoned
  - Pipe networks: ~700 km WW pipes (loss/limited service)
    ~one break per km PW pipes (4000 km)
  - Many CBD buildings, bridges, …
Soils of Christchurch
Ancient Coastlines

(Forsyth et al. 2008)
Regional Soil Stratigraphy
Regional Soil Stratigraphy

(Forsyth et al. 2008)
Regional Soil Stratigraphy

- **Springton Fm**: distal alluvial fans, overbank silt, peat
- **Christchurch Fm**: marine, estuarine, dunes, interdune peat
- **Riccarton Gravel**: outwash gravel and sand, minor overbank silt and peat
Ground Water Table: E-W, along Bealey Ave (north border of CBD)

(Cubrinovski et al. 2011)
Liquefaction: Grain-size Distributions

<table>
<thead>
<tr>
<th>Gravel</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Colloids</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>

Percent Finer by Weight

- Most Liquefiable Soils
- Potentially Liquefiable Soils
- Liquefied soils in Christchurch region

(Tsuchida 1970)

(Pender 2010)
Liquefaction: Darfield Earthquake
Liquefaction: Darfield Earthquake
Liquefaction: Darfield and Christchurch Earthquakes
Severe Liquefaction in Eastern Suburbs

(Mark Quigley: Avonside)
Piles of Liquefaction Ejecta
Evaluation of CPT-Based Liquefaction Triggering Evaluation Procedures
Strong Motion Stations

(Green et al. 2014)
CPT Soundings

(Green et al. 2014)
Case History Sites

(Green et al. 2014)
Estimated PGAs (Bradley, 2014)

$M_w 7.1$ Darfield Earthquake

$M_w 6.2$ Christchurch Earthquake

(Green et al. 2014)

(Green et al. 2014)
Moss et al. (2006): MEA06

(Green et al. 2014)
Ic – FC Correlation (latest version)
Idriss and Boulanger (2008): IB08

(Green et al. 2014)
Conclusion 1

- Based on select case history data from the Canterbury Earthquake Sequence:
  - All of the CPT-base procedures do a reasonable job predicting field observations.
  - Idriss and Boulanger (2008) performed better than the other procedures.

(Green et al. 2014)
Is FS Okay???

Some “rules of thumb” that have been used in the past:

- FS > 1.4: Okay, small strains
- FS > 1.25: Probably okay if consequences are not bad
- FS < 0.9: Problem, go directly to remediation
- 0.9 ≤ FS ≤ 1.25: Marginal, more field testing

What about thickness and depth of the liquefied layer; are these important considerations???
Is FS Okay???

You really need to look at the potential consequences:

- Lateral Spreading
- Flow liquefaction
- Bearing capacity failure
- Post-liquefaction consolidation settlement
- Slope failure
- Buoyant uplift of buried tanks/pipelines
Liquefaction Damage Potential
Liquefaction Potential Index

\[ LPI = \int_{0}^{20 \, m} w(z) \cdot f(z) \, dz \]

- \( f(z) = 0 \) \rightarrow \text{for } FS(z) > 1
- \( f(z) = 1 - FS(z) \) \rightarrow \text{for } FS(z) \leq 1
- \( w(z) = 10 - 0.5z; \ z \text{ in } m \)

(Iwasaki et al. 1978)
Liquefaction Potential (Damage) Index

\[ LPI = \int_{0}^{20 \text{ m}} w(z) \cdot f(z) \, dz \]

Limits:

- \( LPI_{\text{min}} = 0 \) (FS > 1 for \( 0 \leq z \leq 20 \text{ m} \))
- \( LPI_{\text{max}} = 100 \) (FS = 0 for \( 0 \leq z \leq 20 \text{ m} \))

Damage:

- Sand boils: \( LPI \geq 5 \) (3 \( \leq LPI \leq 10 \))
- Lateral spreading: \( LPI \geq 12 \) (5 \( \leq LPI \leq 17 \))

(Holzer et al. 2006)
# Liquefaction Severity

<table>
<thead>
<tr>
<th>Classification</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Manifestation</td>
<td>No surficial liquefaction manifestation or lateral spread cracking</td>
</tr>
<tr>
<td>Marginal Manifestation</td>
<td>Small, isolated liquefaction features; streets had traces of ejecta or wet patches less than a vehicle width; &lt; 5% of ground surface covered by ejecta</td>
</tr>
<tr>
<td>Moderate Manifestation</td>
<td>Groups of liquefaction features; streets had ejecta patches greater than a vehicle width but were still passable; 5-40% of ground surface covered by ejecta</td>
</tr>
<tr>
<td>Severe Manifestation</td>
<td>Large masses of adjoining liquefaction features, streets impassible due to liquefaction; &gt;40% of ground surface covered by ejecta</td>
</tr>
<tr>
<td>Lateral Spreading</td>
<td>Lateral spread cracks were predominant manifestation and damage mechanism, but crack displacements &lt; 200 mm</td>
</tr>
<tr>
<td>Severe Lateral Spreading</td>
<td>Extensive lateral spreading and/or large open cracks extending across the ground surface with &gt; 200 mm crack displacement</td>
</tr>
</tbody>
</table>

(Maurer et al. 2014a)
Observed Liquefaction Severity

M$_{w}$ 7.1 Darfield Earthquake

M$_{w}$ 6.2 Christchurch Earthquake

(Maurer et al. 2014a)
Predicted versus Observed Severity

*Mw* 7.1 Darfield Earthquake

(Maurer et al. 2014a)
Predicted versus Observed Severity

$M_w$ 6.2 Christchurch Earthquake

(Maurer et al. 2014a)
LPI: Darfield and Christchurch Earthquakes

M\textsubscript{w} 7.1 Darfield Earthquake

M\textsubscript{w} 6.2 Christchurch Earthquake

(Maurer et al. 2014a)
# Liquefaction Potential Index

<table>
<thead>
<tr>
<th>Damage Classification</th>
<th>Expected LPI Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Liquefaction</td>
<td>LPI &lt; 4</td>
</tr>
<tr>
<td>Marginal Liquefaction</td>
<td>4 ≤ LPI &lt; 8</td>
</tr>
<tr>
<td>Moderate Liquefaction</td>
<td>8 ≤ LPI &lt; 15</td>
</tr>
<tr>
<td>Severe Liquefaction</td>
<td>LPI ≥ 15</td>
</tr>
<tr>
<td>Lateral Spreading</td>
<td>LPI ≥ 4</td>
</tr>
<tr>
<td>Severe Lateral Spreading</td>
<td>LPI ≥ 4</td>
</tr>
</tbody>
</table>

(Maurer et al. 2014a)
# LPI Prediction Error Classification

<table>
<thead>
<tr>
<th>Error (E) Classification</th>
<th>E (LPI units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excessive Underprediction</td>
<td>E &lt; -15</td>
</tr>
<tr>
<td>Severe to Excessive Underprediction</td>
<td>-15 ≤ E &lt; -10</td>
</tr>
<tr>
<td>Moderate to Severe Underprediction</td>
<td>-10 ≤ E &lt; -5</td>
</tr>
<tr>
<td>Slight to Moderate Underprediction</td>
<td>-5 ≤ E &lt; -1</td>
</tr>
<tr>
<td>Accurate Prediction</td>
<td>-1 ≤ E ≤ 1</td>
</tr>
<tr>
<td>Slight to Moderate Overprediction</td>
<td>1 &lt; E ≤ 5</td>
</tr>
<tr>
<td>Moderate to Severe Overprediction</td>
<td>5 &lt; E ≤ 10</td>
</tr>
<tr>
<td>Severe to Excessive Overprediction</td>
<td>10 &lt; E ≤ 15</td>
</tr>
<tr>
<td>Excessive Overprediction</td>
<td>E &gt; 15</td>
</tr>
</tbody>
</table>

(Maurer et al. 2014a)
Error in LPI Severity Predictions

M$_{\text{w}}$7.1 Darfield Earthquake

M$_{\text{w}}$6.2 Christchurch Earthquake

(Maurer et al. 2014a)
Why is LPI accurate in some regions of Christchurch and not others???
Error in LPI Severity Predictions: Influence of Fines Content

Maurer et al. 2015b

Shoreline ~6000 years bp
True Positive = Liquefaction Predicted and Observed
False Positive = Liquefaction Predicted but Not Observed
Receiver Operating Characteristic (ROC) Analyses

True Positive = Liquefaction Predicted and Observed
False Positive = Liquefaction Predicted but Not Observed
Receiver Operating Characteristic (ROC) Analyses

True Positive = Liquefaction Predicted and Observed
False Positive = Liquefaction Predicted but Not Observed
Receiver Operating Characteristic (ROC) Analyses

True Positive = Liquefaction Predicted and Observed
False Positive = Liquefaction Predicted but Not Observed
Receiver Operating Characteristic (ROC) Analyses

Liquefaction Potential Index (LPI)

Optimum Operating Point (OOP)
LPI = 5

Area Under Curve (AUC) = 1.0
(LPI is the perfect discriminator)
Receiver Operating Characteristic (ROC) Analyses

Liquefaction Potential Index (LPI)

Frequency

0.0 7.5 2.5 5.0 10.0

0.0 0.6 0.8 1.0 0.2 0.4

LPI = 5

Optimum Operating Point (OOP)

LPI = 5???

Area Under Curve (AUC) = 0.5

(LPI is the same as guessing)
Receiver Operating Characteristic (ROC) Analyses

(Maurer et al. 2015b)
ROC Analyses: New Zealand Data

(Maurer et al. 2015a)
Influence of $I_c$ Cutoff: Sites with $I_{c10} < 2.05$

(Maurer et al. 2015b)
Influence of $I_c$ Cutoff: Sites with $I_{c10} > 2.05$
Error in LPI Severity Predictions: Influence of Fines Content

- Result of shortcomings in the FC corrections in the liquefaction evaluation procedures???
- Result of shortcomings in the LPI framework to evaluate severity manifestations for profiles with high FC strata???
No-Liq Layers: Low FC (Ic < 2.05)

<table>
<thead>
<tr>
<th>Dataset Assessed</th>
<th>LPI MODEL</th>
<th>R&amp;W98</th>
<th>MEA06</th>
<th>I&amp;B08&lt;sup&gt;1&lt;/sup&gt;</th>
<th>I&amp;B08&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AUC</td>
<td>OOP</td>
<td>AUC</td>
<td>OOP</td>
<td>AUC</td>
</tr>
<tr>
<td>Liq: Ic &lt; 2.05</td>
<td>0.79</td>
<td>4.0</td>
<td>0.76</td>
<td>5.0</td>
<td>0.83</td>
</tr>
<tr>
<td>Liq: Ic &gt; 2.05</td>
<td>0.79</td>
<td>4.0</td>
<td>0.76</td>
<td>5.0</td>
<td>0.82</td>
</tr>
</tbody>
</table>

(Maurer et al. 2015b)
## Liq Layers: Low FC (Ic < 2.05)

<table>
<thead>
<tr>
<th>Dataset Assessed</th>
<th>LPI MODEL</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R&amp;W98</td>
<td>MEA06</td>
<td>I&amp;B08¹</td>
<td>I&amp;B08²</td>
<td></td>
</tr>
<tr>
<td>No Liq: Ic &lt; 2.05</td>
<td>AUC</td>
<td>OOP</td>
<td>AUC</td>
<td>OOP</td>
<td>AUC</td>
</tr>
<tr>
<td></td>
<td>0.79</td>
<td>4.0</td>
<td>0.76</td>
<td>5.0</td>
<td>0.83</td>
</tr>
<tr>
<td>No Liq: Ic &gt; 2.05</td>
<td>0.67</td>
<td>11.5</td>
<td>0.69</td>
<td>13.5</td>
<td>0.69</td>
</tr>
</tbody>
</table>

(Maurer et al. 2015b)
Conclusion 2

- Based on *thousands* of case history data from the Canterbury Earthquake Sequence:
  - All of the CPT-base procedures do a reasonable job predicting field observations (approx. same AUCs)
  - Idriss and Boulanger (2008) performed better than the other procedures (larger AUC)

- The LPI framework has limitations in predicting severity of surficial liquefaction manifestations for profiles having a fine-grained crust and/or fine-grained layers interbedded with liquefiable layers

(Maurer et al. 2015a,b)
Ishihara $H_1$-$H_2$ Charts

Ishihara (1985)

Ishihara (1996)
Ishihara $H_1$-$H_2$ Charts

What are $H_1$ and $H_2$???
LPI + Ishihara H₁-H₂ Chart = LPI_{ISH}
Ishihara LPI (LPI_{ISH})

ROC Curve

AUC_{LPI_{ISH}} > AUC_{LPI}
Ishihara LPI (LPI_{ISH})

(Maurer et al. 2015c)
Ishihara LPI (LPI_{ISH})

\[
LPI_{ISH} = \int_{H_1}^{20} m F(FS) \frac{25.56}{z} \, dz
\]

\[
F(FS) = \begin{cases} 
1 - FS & \text{if } FS \leq 1 \cap H_1 \cdot m(FS) \leq 3 \\
0 & \text{otherwise}
\end{cases}
\]

\[
m(FS) = \exp \left( \frac{5}{25.56(1-FS)} \right) - 1
\]

(Maurer et al. 2015c)
Ishihara LPI ($LPI_{ISH}$)
Ishihara LPI (LPI_{ISH})

Soil above water table does not liquefy

Calculate:
- $S_{LVD}$
- LPI
- LSN

Potentially liquefiable if subjected to sufficiently strong earthquake shaking

(van Ballegooy et al. 2015)
Ishihara LPI (LPI_{ISH})

<table>
<thead>
<tr>
<th>$a_{max}$</th>
<th>$a_{max} = 0.2g$</th>
<th>$a_{max} = 0.3g$</th>
<th>$a_{max} = 0.45g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_{tans} = 40$</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>$q_{tans} = 80$</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>$q_{tans} = 120$</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
</tbody>
</table>

**Legend**
- $LPI_{ISH}$
- Calculated $LPI_{ISH}$ Values for PL = 50% (where different to those calculated for PL = 15%)
- $q_{tans}$ - Clean sand equivalent normalised CPT penetration resistance
- $a_{max}$ - Peak Earthquake Ground Acceleration

(van Ballegoooy et al. 2015)
Ishihara LPI ($LPI_{ISH}$)

Loma Prieta earthquake: Site LEN-37 – no observed surficial manifestations

(Maurer et al. 2015c)
Ishihara LPI (LPI_{ISH})

Kocaeli earthquake: Site SF-5 – surficial manifestations observed

(Maurer et al. 2015c)
Darfield earthquake: Site AVD-49 – no observed surficial manifestations
(Maurer et al. 2015c)
Ishihara LPI ($LPI_{ISH}$)

Northridge earthquake: Site WYN-5a – surficial manifestations observed

(Maurer et al. 2015c)
Ishihara LPI (LPI$_{ISH}$)

Analysis of 60 cases from around the world

(Maurer et al. 2015c)
Based on sixty worldwide case histories:

- LPI$_{ISH}$ results in predictions that are more inline with field observations than LPI.
- LPI$_{ISH}$ accounts for the influence of the thickness of the non-liquefiable crust, but it does not fully account for fine-grained layers interbedded with liquefiable layers.

(Maurer et al. 2015c)
Aging Effects on Liquefaction

- Temporal gains in the shear strength and stiffness of sands (e.g., increase in CRR)
- Liquefaction triggering curves developed from liquefaction case-histories in Holocene deposits.
  - Adjustments needed for deposits with ages outside range of case-history database

(Maurer et al. 2014b)
Aging Effects on Liquefaction

- Position of triggering curves controlled by youngest, most susceptible deposits
- Reference age likely on order of ~1 to 100 years

\[ \text{CRR}_K = \text{CRR} \times K_{\text{DR}} \]

Age-corrected CRR

\( \frac{\text{CRR at age } t_1}{\text{CRR at “reference age” } t_0} \)

(Maurer et al. 2014b)
Aging Effects on Liquefaction

\[ K_{DR} > 1 \]

- Position of triggering curves controlled by youngest, most susceptible deposits
- Reference age likely on order of \( \sim 1 \) to 100 years

\[ CRR_K = CRR \times K_{DR} \]

age-corrected CRR

\[ \frac{CRR_{t_1}}{CRR_{t_0}} \]

Maurer et al. 2014b
Aging Effects on Liquefaction

Aftershocks: CRR may be reduced after recent liquefaction

\[ K_{DR} < 1 \]

(Maurer et al. 2014b)
Aging Effects on Liquefaction

Deposit Resistance Factor, $K_{DR}$

Time Since Initial Deposition or Prior Liquefaction, $t$ (years)

Hayati & Andrus (2009) Eq. 8
Arrango et al. (2000)

Hayati et al. (2008)

Hayati & Andrus (2009) Eq. 9

Lab curves: reference age very short
Field curves: reference age ~23yrs

(Maurer et al. 2014b)
Aging Effects on Liquefaction

Reference Age $\approx 23$ yrs

Hayati & Andrus (2009) Eq. 9

(Maurer et al. 2014b)
Aging Effects on Liquefaction

CPT Soundings
PGA
Liquefaction Evaluation

Aging Correction Factors
Liquefaction Severity

Do $K_{DR} < 1$ corrections improve accuracy of hazard assessment?

Hayati & Andrus (2009) Eq. 9

$t = 171$ days
$K_{DR} = 0.78$

(Maurer et al. 2014b)
Aging Effects on Liquefaction

Distribution of LPI prediction errors (with/without $K_{DR}$)

Severity of Liquefaction Manifestation: Christchurch Earthquake

- None
- Marginal; No Kdr Correction
- Marginal; Kdr Correction Applied
- Moderate/Severe; No Kdr Correction
- Moderate/Severe; Kdr Correction Applied

Severity of Liquefaction Manifestation: Darfield EQ

- 25th Percentile
- 50th Percentile
- 75th Percentile

(Maurer et al. 2014b)
Distribution of LPI prediction errors (with/without $K_{DR}$)

Severity of Liquefaction Manifestation: Christchurch Earthquake
- None
- Marginal; No Kdr Correction
- Marginal; Kdr Correction Applied
- Moderate/Severe; No Kdr Correction
- Moderate/Severe; Kdr Correction Applied

Severity of Liquefaction Manifestation: Darfield EQ
- None
- Marginal; No Kdr Correction
- Marginal; Kdr Correction Applied

(Maurer et al. 2014b)
$K_{DR}$ correction factors back-calculated such that predictions match the range consistent with marginal manifestation (i.e., $5 < \text{LPI} < 8$)

(Maurer et al. 2014b)
Based on eight case histories from the Canterbury Earthquake Sequence:

- Hazard generally under-predicted without $K_{DR}$ correction
- $K_{DR}$ correction from Hayati and Andrus (2009) typically improved prediction accuracy

(Maurer et al. 2014b)
Summary of Conclusions

- All of the CPT-base procedures do a reasonable job predicting field observations.
- Idriss and Boulanger (2008) performed better than the other procedures.
- The LPI framework has limitations in predicting severity of surficial liquefaction manifestations for profiles having a fine-grained crust and/or fine-grained layers interbedded with liquefiable layers.
- $LPI_{ISH}$ results in predictions that are more inline with field observations than LPI, but does not fully account for fine-grained layers interbedded with liquefiable layers.
- $K_{DR}$ aging correction from Hayati and Andrus (2009) typically improved prediction accuracy for sites of recurrent liquefaction during the Canterbury Earthquake Sequence.
Work in Progress/Future Directions

- Develop a new liquefaction severity index that:
  - Accounts for both the fine-grained crust and fine-grained layers interbedded with liquefiable layers
  - Has depth weighting factors for liquefaction damage potential to shallow and deep foundations and embankments
  - Is completely compatible with liquefaction triggering curve
  - Gives a full quantification of uncertainty
Thank You
References


Next Generation Liquefaction
Field Reconnaissance: Unmanned Aerial Vehicles

Kevin Franke, Ph.D., P.E.
Assistant Professor, CEEn
Brigham Young University
Center for Unmanned Aircraft Systems (C-UAS)

Cooperative Control
- Cooperative timing problems
- Cooperative persistent imaging
- Cooperative fire monitoring
- Consensus seeking

Path Planning
Trajectory Generation
- 3D Waypoint path planning
- Wind compensation
- Collision avoidance
  - Optic flow sensor
  - Laser ranger
  - EO cameras

Image Directed Control
- Image stabilization
- Geo-location
- Vision-aided tracking & engagement

Autonomous Vehicles
- Autopilot design for small UAVs
- Attitude estimation
- Adaptive control
- Tailsitter guidance & control
What is C-UAS? (http://c-uas.byu.edu/)

- **C-UAS**: Center for Unmanned Aircraft Systems
- Sponsored by National Science Foundation under I/UCRC program *and* industry members
- Three universities involved:
  - Brigham Young University
    - Tim McLain, Randy Beard, Mike Goodrich, Eric Mercer, Karl Warnick, John Hedengren, Kevin Franke, Gus Williams
  - University of Colorado
    - Eric Frew, Brian Argrow
  - Virginia Tech is joining us this year!!
Current Industry Membership

- 2D3 Sensing
- AFRL Aerospace Systems Directorate
- AFRL Munitions Directorate
- AAI-Textron
- BP
- Boeing
- Insitu
- L-3 Communications
- NASA Dryden Flight Research Center
- National Oceanic and Atmospheric Administration
- Northrop Grumman
- United Technologies Research Center
- Utopia Compression
- Strong interest from: USBR, Lockheed Martin, URS Corp. Raytheon, Fairweather, and others
Current Project Collaborators

Dr. Ryan Farrell
Computer Science

Dr. John Hedengren
Chemical Engineering
US-89 Arizona Landslide

On February 20, 2013, a massive dry landslide occurred approximately 20 miles south of Page, Arizona. This landslide critically damaged US-89.
Landslide Modeling and Monitoring

In July 2014, we flew the US-89 landslide with a UAV carrying a digital SLR camera. This is an image of the resulting 3D point cloud model.
Landslide Modeling and Monitoring

Recent re-processing of those images produced a model with nearly 950M points (1cm resolution) and median accuracy of 3cm.
Landslide Modeling and Monitoring

We partnered with the UGS and North Salt Lake City to model the recent landslide in August 2014.
Landslide Modeling and Monitoring

The UGS and North Salt Lake City asked us to fly and model the recent landslide in August 2014.
Landslide Modeling and Monitoring
Earthquake Reconnaissance

In April 2014, Dr. Kyle Rollins and I reconnoitered sites in Iquique, Chile following the M8.0 earthquake there. We returned in June with UAVs.
Earthquake Reconnaissance

Here are some screenshots of CV models of liquefaction damage from April 1, 2014 Chile earthquake
Earthquake Reconnaissance

Here are some screenshots of CV models of liquefaction damage from April 1, 2014 Chile earthquake
Earthquake Reconnaissance

Compare the UAV models with this model, developed from handheld photographs (...more photos, actually!) The UAV offers much more coverage.
Earthquake Reconnaissance

Here are some screenshots of CV models of liquefaction damage from April 1, 2014 Chile earthquake
Earthquake Reconnaissance

Here are some screenshots of CV models of liquefaction damage from April 1, 2014 Chile earthquake.
Earthquake Reconnaissance

Here is a screenshot of a CV model of a lateral spread from April 1, 2014 Chile earthquake
Conclusion

• UAVs improve our ability to gather data from post-liquefaction damage sites.

• A large site can typically be reconnoitered and “scanned” in less than 2 hours.

• Utah might consider creating a database of pre-earthquake point clouds for select critical structures. Clouds could be developed using LiDAR or computer vision.
Kevin Franke, Ph.D., P.E.
Assistant Professor, CEEn
Brigham Young University

Next Generation Liquefaction Field Reconnaissance: Unmanned Aerial Vehicles
My Current UAV Platforms:

Rightwing 81” ZXL (a.k.a. “Big Bird”)
- 81” wingspan (very stable!)
- Can fly in 45+ mph winds
- Carries GoPro Hero 3
- Flies at 35-65 mph
- Flight time is 10-20 minutes

Draganfly X-4 Quadcopter
- 4 rotor system
- Very mobile, but squirrely in wind
- Carries GoPro Hero 3 or Panasonic still
- Flies at 0-35 mph
- Flight time is 10-20 minutes

Phantom 2
- 4 rotor system
- Very mobile, more stable than X-4
- Carries GoPro Hero 3
- Flies at 0-35 mph
- Flight time is 10-20 minutes
My Current UAV Platforms:

Skyjib 6 (custom built)

- 6 rotor system
- 360-degree gimbled camera
- GPS waypoint-programmable
- Very mobile, more stable than X-4
- Can carry full-size DSLR camera
- Flies at 0-35 mph
- Flight time is 10-20 minutes

DJI S1000 (octa-rotor)

- 8 rotor system
- 360-degree gimbled camera platform
- GPS waypoint-programmable
- Very mobile, more stable than X-4
- Can carry multiple sensors (e.g., camera & LiDAR)
- Flies at 0-35 mph
- Flight time is 10-20 minutes
My Current UAV Platforms:

Our new addition (....no, we haven’t named her yet!)
Performance-based Assessment of Liquefaction Triggering and Lateral Spread: A Simplified Approach

Levi Ekstrom, Kristin Ulmer, and Dr. Kevin Franke

Utah Liquefaction Advisory Group Meeting

February 9th, 2015
Introduction

- Liquefaction hazards pose a potentially serious problem in Utah
- Benefits of performance-based methods over conventional methods
- Advantages of performance-based methods are within your reach
Outline

• Why Performance-based methods?
  • What are PB methods?
  • How do PB methods differ from conventional methods?
  • Advantages and disadvantages

• Introduction to the Simplified Method
  • Purpose
  • How does it work?
  • Maps

• Validation

• What this means for you

http://liquefactionmitigation.weebly.com/
Why Performance-based Methods?

- **Deterministic** approach: Deterministic Seismic Hazard Analysis (DSHA)

<table>
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<tr>
<th>Seismic Source</th>
<th>Dist (km)</th>
<th>M</th>
<th>PGA</th>
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<td>3. Morgan Fault</td>
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<td>0.0989</td>
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<tr>
<td>4. Great Salt Lake Fault zone, Antelope Section</td>
<td>25.08</td>
<td>6.93</td>
<td>0.1016</td>
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<td>5. Oquirrh-Southern, Oquirrh Mountain Fault</td>
<td>30.36</td>
<td>7.17</td>
<td>0.0958</td>
</tr>
</tbody>
</table>

Estimate 50th or 84th percentile PGA, Mean $M_w$, and Distance

Use DSHA to find the governing fault for your specific location
Why Performance-based Methods?

- **Deterministic** approach

Estimate 50th or 84th percentile PGA, Mean \(M_w\), and Distance

<table>
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<th>PGA</th>
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<td>0.0958</td>
</tr>
</tbody>
</table>

Use DSHA to find the governing fault for your specific location

Deterministic Equations
Why Performance-based Methods?

- **Performance-based Methods**
  - Consider multiple scenarios (R = ?, M_w = ?, a_max = ?) and their respective likelihoods

  Probabilistic Seismic Hazard Analysis (PSHA): develop deaggregations with magnitude, distance, and % contribution

  Develop hazard curves for the parameter of interest

A PSHA considers all the faults in the region
Why Performance-based Methods?

- **Pseudo-probabilistic** approach

Retrieve probabilistic estimate of PGA, Mean $M_w$, and Distance

Deterministic Equations
Why Performance-based Methods?

**Advantages**
- Considers multiple scenarios and their respective likelihoods
- More consistent estimate of hazard
- Return-period based approach for decision-makers

**Disadvantages**
- Requires special training and expertise
- Complex analysis requires time
- Difficult to incorporate into routine projects
- May overpredict liquefaction hazard in some areas of high seismicity
Introduction to the Simplified Method

- Creating the Maps
- Correction Factors
- Parameter Maps vs Hazard Maps
- Comparison of Simplified Methods and Full Performance-Based Methods
The Simplified Method: Creating the Maps

Saturated Sand
\[ \gamma = 19.62 \text{ kN/m}^3 (124.9 \text{ pcf}) \]
\[ (N_1)_{60} = 18, \text{ Fines } < 5\% \]
\[ V_{s,12} = 175 \text{ m/s (574.15 ft/s)} \]
Parameter Maps for:

- Blow counts needed to resist liquefaction ($N_{\text{req\,ref}}$)
- Cyclic Stress Ratio ($\text{CSR}\%_{\text{ref}}$)
- Lateral Spread Displacement ($D_{H\,\text{ref}}$)
The Simplified Method: Liquefaction Assessment

Hazard-targeted map + Site-specific soil data = Site-specific liquefaction initiation results
The Simplified Method: Lateral Spread

Hazard-targeted map + Site-specific data = Site-specific lateral spread results

- Slope
- Free-Face Ratio
- Thickness of Liquefiable Layer
- Fines Content
- Mean Grain Size

Lateral Spread Displacement
\[ D_h^{\text{site}} = 0.126 \text{ m} \]
Parameter Maps vs Hazard Maps

- Single, generic soil profile
- Associated with available soil data
Validation – How Accurate is This Method?

- \( y = 1.0061x \)  \( R^2 = 0.9968 \)
- \( y = 0.9651x \)  \( R^2 = 0.9954 \)
- \( y = 1.0284x \)  \( R^2 = 0.9959 \)

Free Face Profiles  
Ground Slope Profiles  
\( R^2 = 0.9967 \)
What This Means for You...

- You can have the advantages of performance-based methods without the necessary tools, training and expertise
  - With almost none of the disadvantages

- Benefits for Engineers
  - Quickly calculate liquefaction hazards
  - Accurate and simple

- Benefits for Decision-makers
  - Criticality of structure determines hazard level
Questions?

• We would like to acknowledge the DOTs from the following states for supporting our research:
  • Alaska
  • Connecticut
  • Idaho
  • Montana
  • South Carolina
  • Utah
Aspects of research

- Subsurface database construction
- Analysis and map creation
Subsurface Database

- Data collection
  - UDOT, UGS, City Governments, private companies
- Standard Penetration Testing (SPT)
  - 795 data points
- Cone Penetrometer Testing (CPT)
  - 39 data points
## Subsurface Database

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</tr>
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</table>
Subsurface database
Subsurface Database

- 834 total points
Mapping

• Types of maps
  ◦ Liquefaction Triggering Maps
  ◦ Lateral Spread Displacement Hazard Maps
    • Thresholds at 1 cm, 3 cm, and 10 cm
Mapping

- Boulanger and Idriss (2012) liquefaction triggering models
- Aerial lidar data for lateral spread mapping, better topographic models
- Performance-based approach
Timeline

• Subsurface database completed December 2014
• Liquefaction and Lateral Spread maps by July 2015
Liquefaction Hazards – From Mapping to Implementation

Steven F. Bartlett, Ph.D., P.E.
Associate Professor
University of Utah

ULAG 2015
Salt Lake City, Utah
Utah Liquefaction Advisory Group

Members
Steve Bartlett, UU CE, Facilitator
Mike Hylland, UGS liaison
Mark Petersen, USGS liaison
Les Youd, BYU CE
Travis Gerber, BYU CE
Kyle Rollins, BYU CE
Loren Anderson, USU CEE
Jim Bay, USU CEE
John Rice, USU CEE
Aurelian Trandafir, UU G&G
Michael Olsen, UCSD
David Simon, SBI
Grant Gummow, UDOT
Jim Higbee, UDOT
Bill Turner, Earthtec
Ryan Cole, Gerhart-Cole
Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- Estimation of Frequency
- Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- Estimation of Settlement
- Performance-Based Hazard Ordinances
Liquefaction

What is liquefaction?

Before the earthquake:
- Pavement
- Sediment layer
- Water-saturated granular layer

Loosely packed grains. Pore spaces filled with water.

During the earthquake:
- Sand boils
- Sand dike
- Grains pushed apart by upward flow
- Sand injected into overlying sediment
- Tightly packed layer

EARTHQUAKE-INDUCED LIQUEFACTION
Types of Liquefaction Damage

Sand Blow or Sand Volcano

(Image of a modern sand blow with text: "Modern sand blow" and "Liquefied sand" showing a diagram of layers including silt and clay, filled fissure, and liquefied sand, with earthquake waves labeled. Attribution: after Sims and Garvin, 1995.)
Types of Liquefaction Damage

Ground Oscillation

Marina District, San Francisco, 1989 Loma Prieta Earthquake
Types of Liquefaction Damage

- Ground Settlement

2011 Tohoku Earthquake

2010 Christchurch Earthquake
Types of Liquefaction Damage

Bearing Capacity Failure

1964 Niigata, Japan Earthquake
Types of Liquefaction Damage

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.

Lateral Spread

1964 Niigata, Japan Earthquake
Types of Liquefaction Damage

Flow Failure

Lower San Fernando Dam
1971 San Fernando Earthquake

Valdez, 1964 Alaska Earthquake
Topics

- Liquefaction Damage
- **Types of Liquefaction Maps**
- Estimation of Frequency
- Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- Estimation of Settlement
- Performance-Based Hazard Ordinances
Types of Liquefaction Maps

- Liquefaction Susceptibility Maps
- Liquefaction Potential Maps
  - Scenario Maps
  - Probabilistic-Based Maps
- Ground Failure Maps
  - Lateral Spread
  - Ground Settlement
Types of Liquefaction Maps

- Liquefaction Susceptibility Maps
  - Show liquefaction hazard based on susceptibility (soil capacity), but do not consider demand (size of amplitude of strong ground motion)
Types of Liquefaction Maps

- 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 the national seismic hazard maps.

Liquefaction potential for approximate 0.2g pga (Anderson and Keaton)
Types of Liquefaction Maps

- **Ground Failure Maps**
  - Consider liquefaction potential
  - Consider consequences of liquefaction (i.e., displacement)

- Median probabilities of lateral spread displacement for 2,500-year return period seismic event
Types of Liquefaction Maps
(ULAG Maps funded by NEHRP)

- Liquefaction Potential and Ground Displacement Maps
- Seismic Strong Motion (SM) Inputs for Liquefaction Potential Maps
  - M7.0 Earthquake
  - SM with 10% probability of exceedance in 50 years
  - SM with 2% probability of exceedance in 50 years
- Lateral Spread maps (using above scenarios)
- Ground settlement maps (using above scenarios)
- Fully aggregated liquefaction map with PSHA input
  - (see next two slides)
Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- **Estimation of Frequency**
- Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- Estimation of Settlement
- Performance-Based Hazard Ordinances
Estimation of Frequency

How often do bad things happen?

Average return period of event (yrs.)?
### Estimation of Frequency

<table>
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<th>Frequent</th>
<th>Moderately Frequent</th>
<th>Infrequent</th>
<th>Rare</th>
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<td>0 to 500 yrs.</td>
<td>0 to 500 yrs.</td>
<td>500 to 1000 yrs.</td>
<td>1000 to 2500 yrs.</td>
<td>&gt; 2500 yrs.</td>
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1. Frequency of event means that the average return period occurs within that time range. For example, if a frequency range is between 0 to 500 years, this implies that the event has an average repeat time that falls between 0 and 500 years. The frequency of the event must be established by geological/geotechnical evaluations.
Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- Estimation of Frequency
  - Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- Estimation of Settlement
- Performance-Based Hazard Ordinances
Estimation of Frequency 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 Frequency Liquefaction Potential

Recommended “Probabilistic” SPT-Based Liquefaction Triggering Correlation

(For $MW=7.5$ and $\sigma'_V=1.0$ atm)

(Seed et al. 2003)
Estimation of Frequency Liquefaction Potential

- Subsurface data collection
  - Standard Penetration Testing (SPT)
  - Cone Penetrometer Testing (CPT)
Estimation of Frequency Liquefaction Potential

- Subsurface data collection
  - Standard Penetration Testing (SPT)
Estimation of Frequency Liquefaction Potential

- Subsurface data collection
  - Cone Penetrometer Testing (CPT)

Cone Penetration Test (CPT) per ASTM D 5718 procedures

- $f_s = \text{sleeve friction}$
- $u_b = \text{porewater pressure}$
- $q_t = \text{measured tip stress or cone resistance}$
- $q_t = \text{corrected tip stress} = q_c + (1-a_f)u_b$

Continuous Hydraulic Push at 20 mm/s; Add rod every 1 m.

Cone Rod (36-mm diam.)

Readings taken every 10 to 50 mm

$q_t$, $u_b$
Estimation of Frequency Liquefaction Potential

- Subsurface data collection
  - Cone Penetrometer Testing (CPT)
Estimation of Frequency Liquefaction Potential

Geology Map

Borehole Map
Estimation of Frequency (Liquefaction Return Period)

Projection: UTM NAD 83 Zone 12N
Scale: 1:300,000
Road basemap from UDOT

Legend
Liquefaction Probability
Return Period, yr
- > 2500 yr, Low
- 1000 - 2500 yr, Moderate
- 500 - 1000 yr, High
- 0 - 500 yr, Very High
- Special Study Area
Liquefaction Potential Maps (Weber County)

Median probabilities of $P_L$, 500-year seismic event

Median probabilities of $P_L$, 2,500-year seismic event
Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- Estimation of Frequency
- Estimation of Liquefaction Potential
- **Estimation of Ground Displacement**
- Estimation of Settlement
- Performance-Based Hazard Ordinances
Estimation of Ground Displacement


Where:

- \( P(DH>x) \) = The probability of lateral spread exceeding a threshold value (e.g., \( x = 0.1 \text{ m} \) and \( 0.3 \text{ m} \))
- \( P[L | A,M,R] \) = 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 (Salt Lake Valley)


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

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

Free-face ratio: \( W (%) = \frac{H}{L} \times 100 \)
Ground Displacement (Salt Lake Valley)
Lateral Spread or 500 and 2500-year scenarios
Ground Displacement (Salt Lake Valley)
Lateral Spread or 500 and 2500-year scenarios

M 7.0 Lateral spread displacement map
(85 percent chance of non-exceedance)
Estimation of Ground Displacement (Weber Co.)

Gillins and Bartlett (2013) Empirical Model

\[ \log D_H = b_0 + b_{off} x + b_1 M + b_2 \log R^* + b_3 R + b_4 \log W + b_5 \log S + b_6 \log T_{15} + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 + a_5 x_5 \]

\[ x_i = \text{the portion (decimal fraction) of } T_{15} \text{ in a borehole that has a soil index corresponding to the table below} \]

<table>
<thead>
<tr>
<th>Soil Index (SI)</th>
<th>Typical Soil Description in Case History Database</th>
<th>General USCS Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Silty gravel, fine gravel</td>
<td>GM</td>
</tr>
<tr>
<td>2</td>
<td>Coarse sand, sand and gravel</td>
<td>GM-SP</td>
</tr>
<tr>
<td>3</td>
<td>Medium to fine sand, sand with some silt</td>
<td>SP-SM</td>
</tr>
<tr>
<td>4</td>
<td>Fine to very fine sand, silty sand</td>
<td>SM</td>
</tr>
<tr>
<td>5</td>
<td>Low plasticity silt, sandy silt</td>
<td>ML</td>
</tr>
<tr>
<td>6</td>
<td>Clay (not liquefiable)</td>
<td>CL-CH</td>
</tr>
</tbody>
</table>
Ground Displacement (Weber Co.)
Lateral Spread or 500-year scenario

- Median probabilities of exceeding 0.3 m, 500-year event
- 84th percentile probabilities, of exceeding 0.3 m, 500-year event
Ground Displacement (Weber Co.)
Lateral Spread or 2500-year scenario

<table>
<thead>
<tr>
<th>Probability of Exceedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 15 %</td>
</tr>
<tr>
<td>15 - 30 %</td>
</tr>
<tr>
<td>30 - 50 %</td>
</tr>
<tr>
<td>50 - 75 %</td>
</tr>
<tr>
<td>75 - 100 %</td>
</tr>
</tbody>
</table>

North Ogden Landslide - special study area

Median probabilities of exceeding 0.3 m, 2500-year event

84th percentile probabilities, of exceeding 0.3 m, 2500-year event
Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- Estimation of Frequency
- Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- **Estimation of Settlement**
- Performance-Based Hazard Ordinances
Estimation of Settlement

(Tokimatsu And Seed, 1987)
Estimation of Settlement

(Ishihara and Yoshimine 1992).

![Graph showing volumetric strain due to consolidation following liquefaction. The graph includes curves for different Dr values (40%, 50%, 60%, 70%, 80%, 90%) and highlights initial liquefaction points.](image-url)
Settlement (Salt Lake Valley) for 500 and 2500-year scenarios

500-yr event

Legend
- Very High, 0.3 - 0.7 m
- High, 0.1 - 0.3 m
- Moderate, 0.05 - 0.1 m
- Low, 0 - 0.05 m
- Special Study
- Great Salt Lake

2500-yr event

Legend
- Very High, 0.3 - 0.7 m
- High, 0.1 - 0.3 m
- Moderate, 0.05 - 0.1 m
- Low, 0 - 0.05 m
- Special Study
- Great Salt Lake
Topics

- Liquefaction Damage
- Types of Liquefaction Maps
- Estimation of Frequency
- Estimation of Liquefaction Potential
- Estimation of Ground Displacement
- Estimation of Settlement
- Performance-Based Hazard Ordinances
Performance-Based Hazard Ordinances

- What constitutes “acceptable risk?”
- Need a graded, risk-based approach based on performance goals.

- Level of seismic hazard quantified by frequency or return period of event.
- Facilities/structures/systems classified according to importance.

- Performance goals defined for each class
  - Input owners/stakeholders/public
- Performance goal(s) evaluated in design process.
# Classification of Systems

<table>
<thead>
<tr>
<th>Functional Classification</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Critical</strong> (Seismic Use Group III)</td>
<td>Hospitals, fire and police stations, emergency response command and control centers, vital utilities and services.</td>
</tr>
<tr>
<td><strong>Essential</strong> (Seismic Use Group II)</td>
<td>Essential government and commercial facilities. Multi-unit housing. Important cultural and religious facilities. Facilities containing hazardous or toxic substances. Important bridges and major transportation corridors.</td>
</tr>
<tr>
<td><strong>Important</strong> (Seismic Use Group I)</td>
<td>Single unit residential housing. Non-essential commercial facilities and utilities. Secondary streets and transportation arteries.</td>
</tr>
<tr>
<td><strong>Routine</strong></td>
<td>Non-habitable structures (e.g., garages, sheds, storage facilities, etc.) and private roads.</td>
</tr>
</tbody>
</table>
## Safety/Environmental Performance Goals

<table>
<thead>
<tr>
<th>Level</th>
<th>Performance Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>No loss of life or injury to occupants. No release of hazardous or toxic substances.</td>
</tr>
<tr>
<td>Level 2</td>
<td>No significant loss of life or major injury to occupants or significant release of hazardous or toxic substances.</td>
</tr>
<tr>
<td>Level 3</td>
<td>Safety goals are not applicable because these facilities or structures are not used for occupancy.</td>
</tr>
</tbody>
</table>
## Systems Performance Goals

<table>
<thead>
<tr>
<th>Level 1  (Operational)</th>
<th>Facility or structure is <em>functional and operational immediately following the event</em> without interruption or repair.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 2  (Immediate Occupancy)</td>
<td>Facility, structure or system is functional and safe for occupancy soon after the geohazard event without significant loss of function or interruption. Structures should be <em>safe for occupancy and use within days to a few weeks of the event</em> with only minor interruption or repair.</td>
</tr>
<tr>
<td>Level 3  (Damaged/Repairable)</td>
<td>Facility, structure or system is damaged but repairable following the geohazard event with some interruption. <em>Structures should be safe for occupancy or use within several months</em> after the event with major interruption and repair.</td>
</tr>
<tr>
<td>Level 4  (Damaged/Irrepairable)</td>
<td>Facility, structure or system is severely damaged and is not repairable. <em>Structures are not safe for occupancy and not repairable; but have not collapsed.</em></td>
</tr>
</tbody>
</table>
## Performance Goals vs. Event Frequency

<table>
<thead>
<tr>
<th>Functional Classification</th>
<th>Frequency of Geohazard</th>
<th>Safety Performance Goal</th>
<th>System Performance Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical</td>
<td>Frequent</td>
<td>Level 1</td>
<td>Level 1</td>
</tr>
<tr>
<td></td>
<td>Moderately Frequent</td>
<td>Level 1</td>
<td>Level 1</td>
</tr>
<tr>
<td></td>
<td>Infrequent</td>
<td>Level 1</td>
<td>Level 1</td>
</tr>
<tr>
<td></td>
<td>Rare</td>
<td>Level 1</td>
<td>Level 1</td>
</tr>
<tr>
<td>Essential</td>
<td>Frequent</td>
<td>Level 1</td>
<td>Level 1</td>
</tr>
<tr>
<td></td>
<td>Moderately Frequent</td>
<td>Level 1</td>
<td>Level 1</td>
</tr>
<tr>
<td></td>
<td>Infrequent</td>
<td>Level 2</td>
<td>Level 2</td>
</tr>
<tr>
<td></td>
<td>Rare</td>
<td>Level 2</td>
<td>Level 3</td>
</tr>
<tr>
<td>Important</td>
<td>Frequent</td>
<td>Level 1</td>
<td>Level 1</td>
</tr>
<tr>
<td></td>
<td>Moderately Frequent</td>
<td>Level 1</td>
<td>Level 1</td>
</tr>
<tr>
<td></td>
<td>Infrequent</td>
<td>Level 2</td>
<td>Level 3</td>
</tr>
<tr>
<td></td>
<td>Rare</td>
<td>Level 2</td>
<td>Level 4</td>
</tr>
<tr>
<td>Routine</td>
<td>Frequent</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Moderately Frequent</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Infrequent</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Rare</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
2015 UTAH LIQUEFACTION ADVISORY GROUP (ULAG) MEETING

David B. Simon
Simon Associates LLC

Alan Taylor
Taylor Geotechnical
1. Current issues and problems in addressing liquefaction related to geologic hazard ordinances.

2. Development of geologic hazards ordinances.

3. Data collaboration.
Having been involved in the drafting of two municipal geologic hazardous ordinances, the primary issue appears to be municipalities reluctance/refusal to establish a geologic hazard ordinance … not necessarily issues and problems in addressing liquefaction in a geologic hazard ordinance.

In regards to issues and problems in addressing liquefaction in a geologic hazard ordinance … DATA.
History of geologic ordinances at Draper City and Morgan County would be appropriate and effective examples
**LIQUEFACTION REFERENCES**

*Initial Anderson Studies*


LIQUEFACTION REFERENCES - continued

Subsequent Studies


Southern Utah


LIQUEFACTION REFERENCES - continued

Recent Folio Maps

- Castleton, J.J., Elliott, A.H., and McDonald, G.N., 2011, Geologic hazards of the Magna quadrangle, Salt Lake County, Utah: Utah Geological Survey Special Study 137, 73 p., 10 plates, scale 1:24,000, CD.


Compilation

Municipalities with Comprehensive Prescriptive Geologic Hazard Ordinances

1. Salt Lake County
2. Draper City
3. Morgan County
4. Iron County
Geologists are “scientists” with an unnatural obsession with rocks and alcohol. Often too intelligent to do monotonous sciences like biology, chemistry, or physics, geologists devote their time to mud-worrying, volcano spotting, fault poking, skiing, bouldering, dust-collecting, and high-risk coloring.
Anti-Regulatory Development Attitude When Draper City and Morgan County Entered into the Process

1. Utah is a “property rights” state.

2. Many state legislators are developers, builders, real estate agents.

3. Developers question a municipality’s role/rights in reviewing a private developer’s consultant’s work.
Draper City Review Process

- Prior to 2003 Draper City “blindly” accepted reports from “professionals” without clear and concise prescriptive minimum standards and/or a formalized review process.

- In 2003, Draper City initiated a geologic review process via adoption of the Salt Lake County geologic hazards ordinance, which included inconsistent review by City consultants.
Draper City Review Process – continued

- Revised Geologic Hazard Ordinance in 2006 – resulted in the most comprehensive geologic hazard ordinance in Utah and was used as the model ordinance by the Governor’s Geologic Hazards Working Group.

- In 2007, Draper City initiated thorough geologic reviews.
In 2004, existing Ordnance in place – two issues, County not requiring geologic review as stipulated and ordinance allowed approval of subdivisions with restricted “R” lots.

October 17, 2006 created a building moratorium in specific subdivisions in the Mountain Green area County Ordinance No Co-06-22.

New ordinance adopted June 1, 2010, which effectively removed geologic review in lieu of “Professional Certification.”
MORGAN COUNTY CERTIFICATION

- A written, stamped certification from a professional geologist and engineer, licensed in the state of Utah, that:

  - The geologic hazard reports have been prepared pursuant to the requirements of this article;

  - Every proposed development lot or building pad does not present an unreasonable or unacceptable risk to the health, safety, and welfare of persons or property ... because of the presence of geologic hazards or because of modifications to the site due to the proposed land use;

  - Every proposed development lot or building site demonstrates that, consistent with the state of the practice, the identified geologic hazards can be mitigated to a level where the risk to human life and damage to property are reduced to an acceptable and reasonable level in a manner which will not violate applicable federal, state, or local statutes, ordinances or regulations.
A mitigation plan that demonstrates that the identified hazards or limitations will be addressed without impacting or adversely affecting off site areas. Mitigation measures must be reasonable and practical to implement and shall not require ongoing maintenance by property owners; and

Verification from the issuer of professional errors and omissions liability insurance, in the amount of one million dollars ($1,000,000.00), which covers the preparer of the statements from the licensed geologist and engineer, and which are in effect on the date of preparation of all required reports and certifications.

Morgan County may set other requirements as are necessary to mitigate any geologic hazards and to ensure that the purposes of this article are met. These requirements may include, but are not limited to ...
MORGAN COUNTY CERTIFICATION - continued

1. Additional or more detailed studies and professional certifications to understand or quantify the hazard or determine whether mitigation measures recommended in the report are adequate;

2. Specific mitigation requirements; establishing buildable and nonbuildable areas; limitations on slope grading and controls on grading, or revegetation;

3. Prior to receiving a grading, excavation, or building permit, final grading plans, when required, shall be prepared, signed and sealed by the licensed professional engineer and the engineering geologist and geotechnical engineer that prepared the geologic hazards and geotechnical report(s) to verify that their recommendations have been appropriately incorporated in the final grading plan and that building locations are approved;
4. As built grading plans, when required, shall be prepared, signed and sealed by the licensed professional engineer and the engineering geologist and geotechnical engineer that prepared the geologic hazards and geotechnical report(s) to verify that their recommendations have been appropriately incorporated and that building locations are approved, prior to the issuance of a building permit;

5. Grading plans, when required, shall include, at a minimum, the following:

   a. Maps of existing and proposed contours;
   b. Present and proposed slopes for each graded area;
   c. Existing and proposed drainage patterns;
   d. Location and depth of all proposed cuts and fills;
   e. Description of methods to be employed to achieve stabilization and compaction;
   f. Location and capacities of proposed drainage, structures, and erosion control measures based on maximum runoff for a 100-year storm;
   g. Location of existing buildings or structures on or within one hundred feet (100') of the site, or which may be affected by proposed grading and construction; and Plan for monitoring and documentation of testing, field inspections during grading, and reporting to Morgan County;
6. Installation of monitoring equipment and seasonal monitoring of surface and subsurface geologic conditions, including groundwater levels; and

7. Other requirements such as time schedules for completion of the mitigation and phasing of development.

C. Morgan County may also set requirements necessary to protect the health, safety, and welfare of the citizens of Morgan County, protect Morgan County's infrastructure and financial health, and minimize potential adverse effects of geologic hazards to public health, safety, and property as a condition of approval of any development which requires a geologic hazards report.

D. Morgan County may require the engineering geologist and geotechnical engineer that prepared the geologic hazards and geotechnical report(s) be on site, at the cost of the applicant, during certain phases of construction, particularly during grading phases and the construction of retaining walls.
ISSUES TO OVERCOME

- City leadership and willingness to leap into “regulation.”
- Recognition that previous procedures were woefully inadequate.
- “Education” of City officials the general geologic review processes -using examples from surrounding communities where geologic issues were ignored is important.
- Commitment by City leadership to support staff and the regulatory review process.
SUMMARY

The Draper City ordinance *works and works well* because Draper City has established a clear and concise set of prescriptive minimum standards. Developers and their consultants now know the “rules.”

The Morgan County ordinance works and works well when properly implemented and supported by County Council.
The success of a geologic hazard program has, and continues to be, directly proportional to City/County officials, administrators, and planners ability to understand geologic processes. Other factors include:

- review-consultants who understand City processes and can circumvent potential issues that could adversely impact the City;

- making the hard decisions in regards to development, even if it involves halting approved developments;

- advocating with the State legislature to assure a municipality’s right to geologic and geotechnical review and the protection of public health, safety and welfare.
Challenges faced by the municipalities during successful implementation of a geologic hazard ordinance include the continued outrage by the development community (including likely litigation), resistance by Consultants, and continued attempts by the development community to take control of the development process.

Less resistance from the consulting community and implementation of a continuing education requirement would greatly contribute to achieving a municipality’s mandate of protecting public health, safety, and welfare.
Work to be done includes educating cities without an ordinance of the need and benefits of a prescriptive geologic hazard ordinance.
Thank You

Questions?

I HATE LAND. CAN YOU CROSS-TRAIN ME TO BE AN ENGINEER?

ABSOLUTELY. ALL YOU NEED IS A TIME MACHINE AND A BRAIN WITH TWICE AS MANY FOLDS AS YOUR CURRENT MODEL.

MAYBE I COULD TRY GEOLOGY. THAT'S JUST LIQUOR AND GUESSING.
Collaboration of Data

Alan Taylor
Taylor Geotechnical