Update on Pilot Program to Assess Seismic Hazards in the St. Louis Metro Area

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Earthquakes Mean Business
February 6, 2009
Step 1

Construction of a Virtual Geotechnical Database for the Geology Underlying the St. Louis Metropolitan Area
The St Louis study area consists of 29 USGS 7.5 minute Quadrangles in Missouri and Illinois, encompassing 4,482 sq km land area

The area consists of: floodplains along the rivers; and loess-covered elevated uplands on either side.

Earthquake liquefaction features have been identified along the major river channels; some are interpreted as having formed in 1811-1812.
Seven GIS Geodata layers underlying the St. Louis Metro Area

We collected and/or estimated the following information:
- 1) Surficial geology
- 2) Loess thickness
- 3) Bedrock geology
- 4) Borehole information
- 5) Shear wave velocities of surficial materials
- 6) Depth to groundwater
- 7) Depth to Paleozoic age bedrock

Goal is to estimate the severity of shaking:
- Amplification of incoming seismic energy due to soil cap overlying dense Paleozoic age bedrock
- Magnification of incoming seismic energy due to impedance contrast with the soil cap
Loess (Peoria and Roxana Silts):

- Thickest along the river bluffs bordering the Missouri and Mississippi Rivers;
- Thins exponentially, away from the river bluffs.
Map Scale Matching Problems

Possible Solutions:

For mismatching boundary area, editing another 24K map boundaries instead of 100K map
Borehole Locations

- **Data Sources:**
  - MoDNR-DGLS
  - ISGS

- **Note** Data Gaps in Jefferson and eastern St. Charles counties

<table>
<thead>
<tr>
<th>Geotechnical boring (MoDGLS)</th>
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<tbody>
<tr>
<td>Borehole Type</td>
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<tr>
<td>▪ Bedrock depth and type</td>
</tr>
<tr>
<td>▪ Corelog (RQD)</td>
</tr>
<tr>
<td>▪ Grain Size</td>
</tr>
<tr>
<td>▪ Material</td>
</tr>
<tr>
<td>▪ Physical property</td>
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<td>▪ Water observation</td>
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<table>
<thead>
<tr>
<th>Geotechnical boring (ISGS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole Type</td>
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<tr>
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</tr>
<tr>
<td>▪ Highway/Engineering</td>
</tr>
<tr>
<td>▪ Highwayhead</td>
</tr>
<tr>
<td>▪ Log</td>
</tr>
<tr>
<td>▪ Water well</td>
</tr>
</tbody>
</table>

*Vector data model*
# Borehole Information

- Data Sources (Digital Format); MoDNR-DGLS and ISGS

<table>
<thead>
<tr>
<th>State</th>
<th>Borehole type</th>
<th>Number of records</th>
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<tr>
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<td>Corelog</td>
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<td>Core recovery (%), Rock Quality Designation (RQD)</td>
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<td></td>
<td>Grain Size</td>
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<td>Grain size analysis of soil</td>
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<td>Material</td>
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<td>Description of soil material</td>
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<td></td>
<td>Physical Property</td>
<td>1906</td>
<td>Standard Penetration Test (SPT) N-value, Cone Penetration Test (CPT), ASTM class, Unit weight (water content, %), Liquid limits, and Plastic index</td>
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<td>Depth to groundwater</td>
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<td>Site</td>
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<td>2394</td>
<td></td>
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<td>Illinois</td>
<td>Highway Log</td>
<td>857</td>
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<td>Highway Head</td>
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<td>Log</td>
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<td>Water Well</td>
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<tr>
<td>Site</td>
<td></td>
<td>4817</td>
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</table>
Locations of Shear Wave Velocity (Vs) Measurements

Data Sources (119):
- ISGS (3)
- UMR (99)
- USGS (17)
- More being added to the database from private sector consultants
Examples

Vs Reference Profiles and Soil Columns derived from adjacent boreholes

Vs Profile-Cahokia Clayey (Monk Mound, Granite City, Cahokia Quads)

Shear Wave Velocity (m/s)

Depth (m)

Vs Profile-Loess in Illinois

Shear Wave Velocity (m/s)

Depth (m)

Vs Profile-Cahokia Sandy (Monk Mound & Granite City Quads)

Shear Wave Velocity (m/s)

Depth (m)

Vs Profile-Loess in St. Louis

Shear Wave Velocity (m/s)

Depth (m)
Geospatial Prediction of the Groundwater Table

Application: important consideration in engineering and environmental decision making; for

- waste disposal sites
- natural hazards, such as shaking-induced soil liquefaction, and lateral spreads.
General Specifications of the Groundwater Table

The groundwater table elevation generally meets the following specifications:

1) follows the shape of the land surface
2) is equal to the ground elevation at streams,
3) the depth to groundwater table is deepest in hilly area

DTW: Depth to Groundwater; DTW 1 > DTW 2
Profile of Groundwater Table (W) with and without considering the ground surface (G)

- Estimated W without considering G
  - Using kriging

- Estimate W concerning G and constraining W=G
  - Using cokriging
Input data for Modeling Groundwater Table

- Observation Well
- Data Point for Obtaining Water Elevation at Streams and Rivers
- Major River
- Stream
Kriging Map of Predicted Groundwater Table Elevation

Raster data model

Standard Error Map Using Kriging

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Cokriging Map of Groundwater Table

Primary variables:
- 1,052 well logs
- 2,569 artificial data points along drainage.

Secondary variables:
- Resolution/accuracy of actual ground elevations (500m × 500m grids), extracted from USGS Digital Elevation Models
2) Cokriging Map of Predicted Groundwater Table

Cokriging Map of Predicted Groundwater

Standard Error Map Using Cokriging

Raster data model

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Problems with interpolating the bedrock Surface beneath the ground

In undulating terrain, the **bedrock surface** is often a complex, undulating feature, shaped by previous erosional and deformational events

- Linear interpolations between adjacent data points in rugged terrain often lead to erroneous results, because:
  - 1) overestimation of bedrock surfaces in paleovalley systems
  - 2) a local contouring model may result in poor estimates when applied to a different geomorphic province or terrain
Procedure for Interpolating Depth-to-Bedrock

3) Of these two approximations, our model was programmed to select the *deeper bedrock surface*, which we feel is more accurate.
Kriging Map of Bedrock Elevation

subtracted DEM from kriged Depth-to-Bedrock
Step 2

Preliminary Assessment of Soil Liquefaction Potential
Liquefaction is a soil failure mechanism that occurs when saturated cohesionless soil loses shear strength. This occurs when the soil pore pressure exceeds the effective confining stress.

It often occurs in loose unconsolidated sands during earthquake-induced ground shaking, and behaves like a fluid.

When the water pressure increases and sand is liquefied, a slurry of sand/water is forced to the ground surface.
Locations of 564 Borings used to calculate the Liquefaction Potential Index, or LPI

- Data Sources (Boring information):
  - MoDNR-DGLS, ISGS
## Historical Liquefaction Severity
Assessed from LPI (Iwasaki, 1982)

<table>
<thead>
<tr>
<th>LPI</th>
<th>Severity of Liquefaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>None</td>
</tr>
<tr>
<td>$0 &lt; \text{LPI} \leq 5$</td>
<td>Little to none</td>
</tr>
<tr>
<td>$5 &lt; \text{LPI} \leq 15$</td>
<td>Moderate</td>
</tr>
<tr>
<td>$15 &lt; \text{LPI} \leq 100$</td>
<td>Severe</td>
</tr>
</tbody>
</table>

- The LPI technique evaluates the entire soil column overlying the stable bedrock.
- The higher the LPI value, the more severe liquefaction damage.
Where the mixture of a **liquefiable** and non-liquefiable soil layer exists at a single boring,

**Will liquefaction occur?**

**If so, how severe is the liquefaction?**
The LPI Method allows us to subjectively grade the severity of liquefaction potential. LPI = 6.2 in this soil column; therefore, liquefaction is likely to occur.

Liquefaction severity will be “MODERATE”, based on historical liquefaction evidences (Iwasaki et al., 1982).
LPI estimates for various Earthquake Scenarios

Liquefaction potential in the upper Mississippi Embayment may not be a significant issue at Magnitudes < 6.4 (Obermeier, 1989; Tuttle and Schweig, 1995)

LPI values from 564 data points were calculated for a M7.5 quake with PGA values of 0.10g to 0.30g (Toro and Silva, 2001), emanating from the New Madrid Seismic Zone
Liquefaction Potential Map (inferred from LPI) for M7.5 with 0.10 PGA

Severe Liquefaction Potential Area (LPI>15):
- Alluvial fans in part (where, gwt<0.5m) in Illinois
- Near confluence of Mississippi-Illinois rivers

Grey areas have insufficient number of borings to analyze
Liquefaction Potential Map (inferred from LPI) for M7.5 with 0.20 PGA

- **Severe Liquefaction Potential Area** (LPI>15):
  - Alluvial fan in part (gwt<4.7m) in Illinois
  - Alluvium in part (gwt<4.4m) along major rivers and streams
  - Clayey alluvium (gwt<4.6m) and sandy alluvium (gwt<5.1m) in ox bow & adjacent alluvial fan
Step 3

Physical Factors Affecting Seismic Site Response
What is Site Response? How the soil under the site affects the intensity of ground shaking.

The type, depth and size of fault, combined with physical properties of crust and geophysical properties of the surficial soils affect **site response**.
Ground Motion Parameters

Peak Ground Acceleration (PGA) is the maximum acceleration experienced by the particle during the course of the earthquake motion.

Spectral Acceleration (SA) is what is experienced by a building, as modeled on a massless vertical rod, having the same natural period of vibration as the building.
Estimating surface accelerations

Surface accelerations can be estimated using 1-D seismic site response software.

Typical input data includes:
- Soil physical properties
- Soil dynamic properties
- Soil thickness
- Input rock motion at the base of the soil column

These are combined to estimate the site amplification, or de-amplification.
Magnitude 6.8 quake emanating from South Central Illinois at 110 km
The spectral acceleration value varies with the natural period of the structure.
Effect of Soil Thickness on RESPONSE SPECTRA

Soil Thickness: 28 m
Peak SA = 0.28 g  
Peak Period = 0.62 sec

Soil Thickness: 25 m
Peak SA = 0.35 g  
Peak Period = 0.51 sec

Soil Thickness: 22 m
Peak SA = 0.28 g  
Peak Period = 0.45 sec

Soil Thickness: 39 m
Peak SA = 0.26 g  
Peak Period = 0.87 sec
Variation in expected *spectral acceleration* with *alluvial thickness* in the St Louis, MO area
Step 4

Distribution of Site Amplification and Development of Site Amplification Maps
The Missouri S&T pilot study sought to develop the following maps, of a ~460 km$^2$ land area:

1) **Site amplification maps** for different levels of ground shaking (0.01, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0) in terms of PGA, 0.2 sec and 1 sec spectral accelerations.

2) **2%** probability of exceedance in 50 years in terms of PGA;

3) **5%** probability of exceedance in 50 years in terms of PGA;

4) **10%** probability of exceedance in 50 years in terms of PGA;

5) **0.2 second** spectral accelerations for 2%, 5% and 10% probabilities of exceedance in 50 years;

6) **1 second** spectral accelerations for 2%, 5% and 10% probabilities of exceedance in 50 years;

7) 2 scenario earthquakes ($M_o$ 7.0 and 7.7) and their associated **PGA** and **0.2 sec-SA and 1 sec-SA**;
What information do we need to estimate site amplification?

1) Characterize the shallow geology overlying the bedrock
   - Surficial geology maps
   - Depth to Bedrock

2) Characterize the bedrock acceleration

3) Characterize the thickness and shear wave velocity of the bedrock underlying the surficial materials

4) Characterize the properties of the surficial materials (~soil cap)
   - Physical soil properties
   - Dynamic soil properties (shear modulus and damping, shear wave velocity)
Digital Elevation Model used in pilot study
Depth to Bedrock (Surficial Geology Thickness Map)
Drawbacks

When the bedrock surface is uniform there is little uncertainty in the calculations. However, large variations in the data within small distances make predictions less certain.

The loess deposits mantling the uplands tend to thicken towards hilltops and thin towards valleys, because of erosion.

When thickness data is missing in these valleys, kriging techniques can be unreliable, as shown at lower right.
Surficial Geology of St. Louis study area
Typical cross section thru Mississippi River flood plain

Peoria and Roxana Silt and wind-blown loess

Cahokia Formation (Cc, Cs)

Glasford formation -till

Henry Formation (h)
Boreholes Used in the pilot study
Estimation of Top-of-Bedrock Elevations

Legend
Top of Bedrock Elevation Prediction Map
in meters
Filled contours
- 47 - 60
- 60 - 70
- 70 - 80
- 80 - 90
- 90 - 100
- 100 - 110
- 110 - 120
- 120 - 130
- 130 - 140
- 140 - 163

COLUMBIA BOTTOM
WOOD RIVER
GRANITE CITY
MONKS MOUND

Kilometers
Cross sections with estimates of uncertainty
Bedrock properties

We used 1750 m/sec +/- 250 m/sec for the weathered bedrock shear-wave velocity, suggested by seismologist Robert Herrmann at St. Louis University.

We selected 0m / 2m / 20 m thicknesses for the weathered bedrock.

We also used 2800 m/sec for the half-space below the weathered bedrock.
Characteristic Vs profiles were developed for nine geologic/geomorphic terrains, such as alluvial or loess/colluvial covered uplands, etc.
Floodplain (Alluvial) deposits

Characteristic Vs Profiles

- \( V_s = 134 \text{ m/s} \), \( \sigma = 33 \text{ m/s} \)
- \( V_s = 180 \text{ m/s} \), \( \sigma = 30 \text{ m/s} \)
- \( V_s = 218 \text{ m/s} \), \( \sigma = 34 \text{ m/s} \)
- \( V_s = 250 \text{ m/s} \), \( \sigma = 50 \text{ m/s} \)
- \( V_s = 256 \text{ m/s} \), \( \sigma = 50 \text{ m/s} \)
- \( V_s = 286 \text{ m/s} \), \( \sigma = 53 \text{ m/s} \)

Shear-wave velocity (m/sec)

Depth (m)
Loess-covered Upland deposits

Characteristic Vs Profiles

- \( V_s = 179 \text{ m/s} \)
  - \( \sigma = 51 \text{ m/s} \)

- \( V_s = 241 \text{ m/s} \)
  - \( \sigma = 86 \text{ m/s} \)

- \( V_s = 325 \text{ m/s} \)
  - \( \sigma = 116 \text{ m/s} \)

- \( V_s = 442 \text{ m/s} \)
  - \( \sigma = 167 \text{ m/s} \)

- \( V_s = 481 \text{ m/s} \)
  - \( \sigma = 211 \text{ m/s} \)

- \( V_s = 539 \text{ m/s} \)
  - \( \sigma = 217 \text{ m/s} \)
Comparisons between Vs profiles for Alluvium in the major river valleys and the Loess covered uplands
For every grid point, calculations were performed 100 times for the 10 ground-motion levels and three ground motion parameters (PGA, 0.2sec Sa, and 1 sec Sa), bringing the total to 3000 calculations per grid point.

When multiplied to the total number of grid points, more than 5,400,000 calculations were made.

Total of 1,974 grid points, 500 m apart
Step 6

Distribution of Site Amplification
Distribution of Site Amplification in Alluvium
Distribution of Site Amplification in Loess
Soil Cap Thickness vs. Ground motion

Upland Profiles

Floodplain Profiles
Site amplification maps were generated for discrete increments of ground motion (0.01 to 1.0 g) and for the following ground motion parameters:

- Peak Ground Acceleration (PGA)
- 0.2 second Spectral Acceleration
- 1.0 second Spectral Acceleration
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Site amplification depends on the severity of the assumed input ground motion.

Site amplification also depends on the geologic conditions underlying any given location.

Site Amplification is severe on upland sites underlain by thick deposits of loess.

Site Amplification is also severe for long period structures on deep (>~20 m) alluvial sites, in the major river flood plains.
Left – Deeper alluvial cover (~31 m) tends to magnify long period (SA 1.0 sec) motions

Middle – Medium alluvial cover (~18 m) tends to magnify motions for 0.2 sec SA

Right – Upland sites mantled by loess tend to magnify bedrock motion because of impedance contrast between bedrock and soil cap.
Seismic Hazard Maps

Previous Examples:

- National Seismic Hazard Maps (2002)
- Memphis Shelby County Seismic Hazard Maps (2004)
The National Seismic Hazard Maps were constructed using the best earth science information available. However, they do NOT include the effects of local soils, or so-called “site effects”
These include the effects of variations in local geology.

Are completely consistent with the national maps.

The scale is useful locally, but not intended to be site-specific.

Urban Seismic Hazard Maps (Memphis and St Louis)
As much as 300% greater accelerations in loess
As much as 200% greater accelerations in alluvium

<table>
<thead>
<tr>
<th>PGA (g)</th>
<th>Alluvium</th>
<th>Loess</th>
</tr>
</thead>
<tbody>
<tr>
<td>2%-in-50</td>
<td>Max</td>
<td>0.383</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>0.267</td>
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<tr>
<td></td>
<td>Mean</td>
<td>0.333</td>
</tr>
</tbody>
</table>
As much as 200% greater accelerations in loess
As much as 20% lower accelerations in alluvium, locally.

<table>
<thead>
<tr>
<th>0.2 sec SA</th>
<th>Alluvium</th>
<th>Loess</th>
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</thead>
<tbody>
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<td>2%-in-50</td>
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<td></td>
</tr>
<tr>
<td>Max</td>
<td>0.783</td>
<td>0.965</td>
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<tr>
<td>Min</td>
<td>0.407</td>
<td>0.422</td>
</tr>
<tr>
<td>Mean</td>
<td>0.511</td>
<td>0.750</td>
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</table>
Summary: Shaking intensity is controlled by the underlying geology

2% probability of exceedance in 50 years acceleration values for loess at 0.2 sec Sa and for alluvium at 1 sec Sa values appear to be large enough to cause structural damage in the St. Louis Metro Area.

Earthquake forces may be most severe for short period structures, on upland sites underlain by loess.

Earthquake forces may also be severe for long period structures on deep (>14 m) alluvial sites, in the natural flood plains.
Late Pleistocene and Holocene Alluvial thickness appears to be the key factor in controlling local intensity of seismic site response.
The results indicate that the site amplification on alluvial sites is most influenced by the unit thickness. Therefore, more data is needed to better define the variations of thickness in alluvium.

The depth to top-of-bedrock (soil cap thickness) map was prepared using kriging methods. There are inherent advantages and disadvantages associated with this methodology. Every effort should be made to amend this map with additional data and hand-estimate the bedrock topography, in lieu of kriging, to elicit a more accurate prediction (ignoring 3D effects).
Site amplification and seismic hazard depend largely on the estimated input parameters. Some of these parameters must be estimated more accurately, i.e., maps showing thickness of the soil cap.

The hazard results are based on the 2002 USGS model. The USGS has since updated their models with a new National Map in 2008. New calculations need to be performed to evaluate how these changes compare with the estimates in the Missouri S&T study.
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This lecture will be posted at:

http://web.mst.edu/~rogersda/nmsz/