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

Earthquakes
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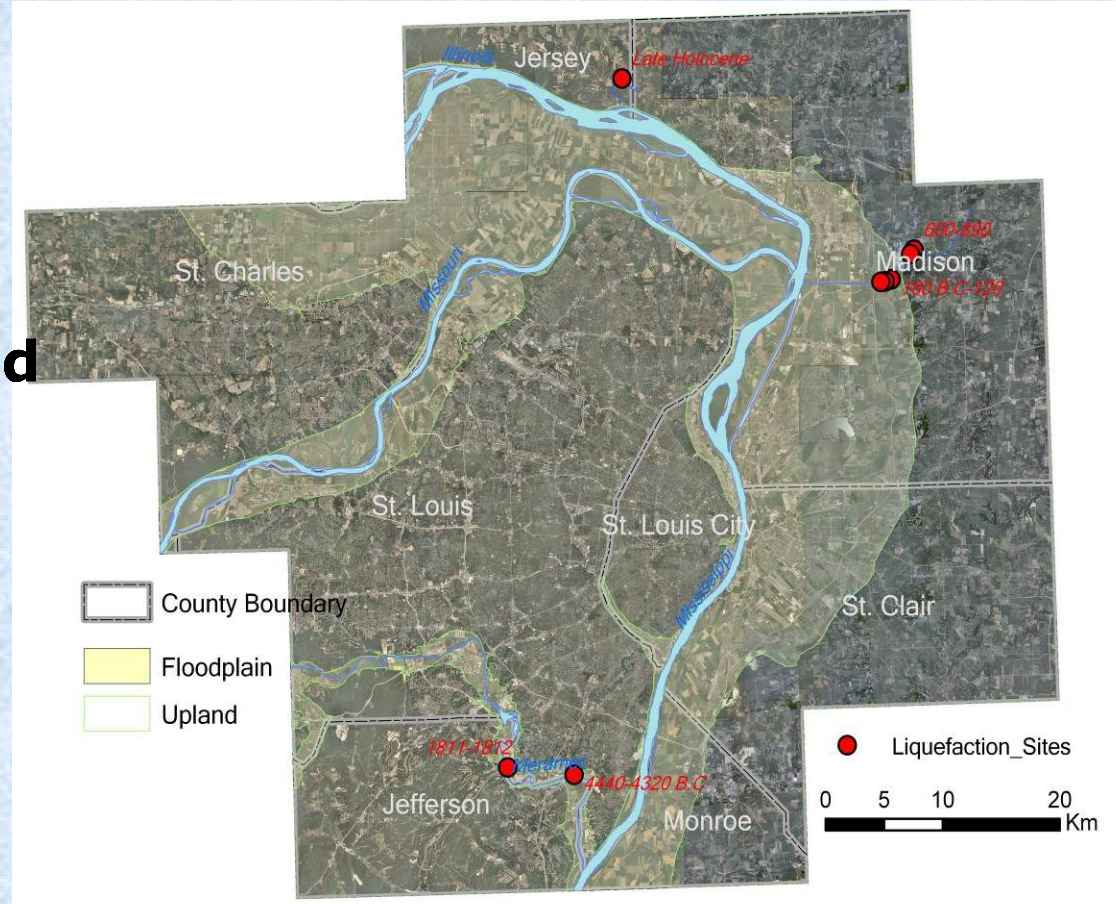
The St Louis study area consists of 29 USGS 7.5 minute Quadrangles in *Missouri* and *Illinois, encompassing 4,482 sq km land area*

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*

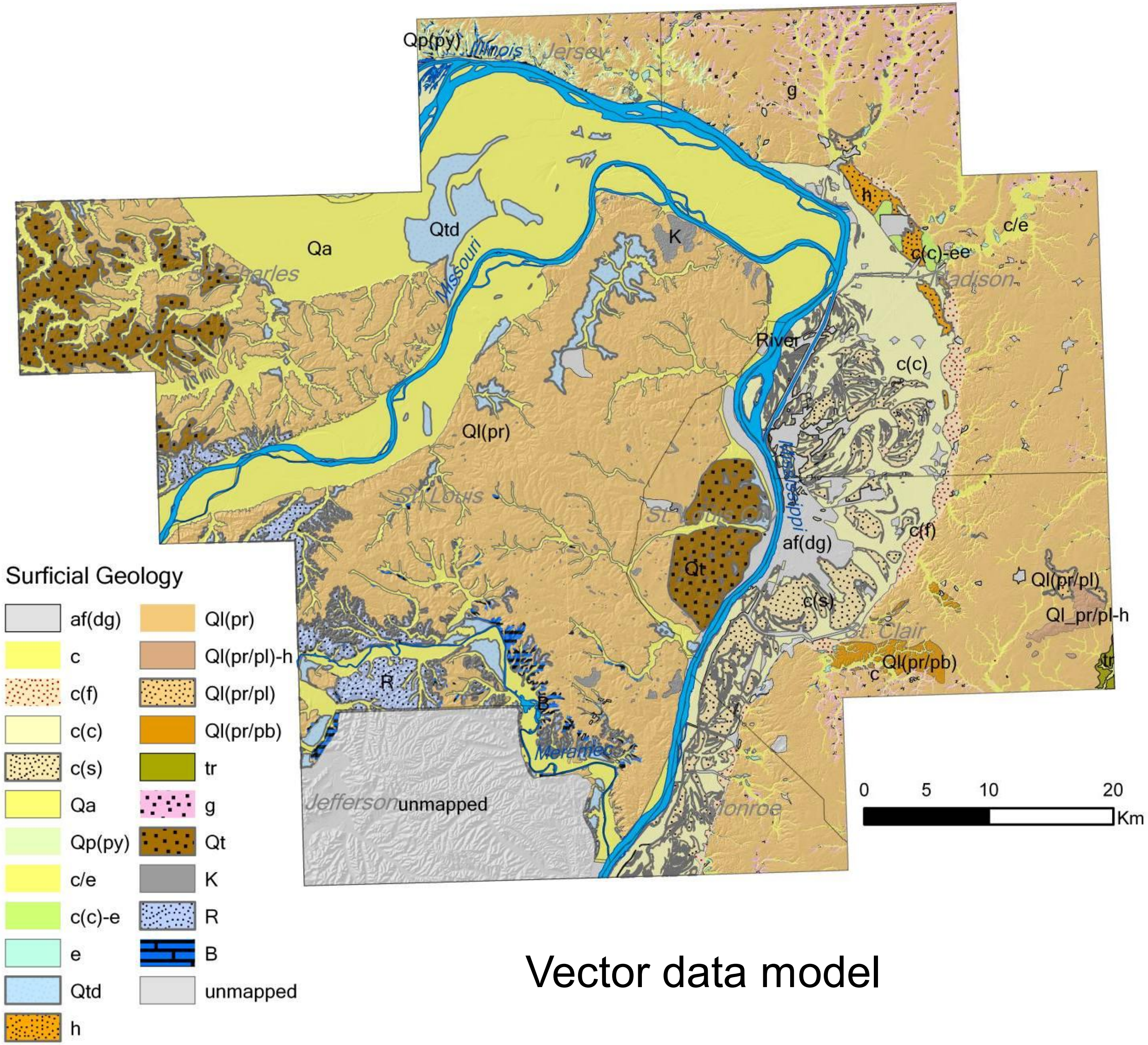
We collected and/or estimated the following information:

- 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**

Compiled Surficial Geologic Map



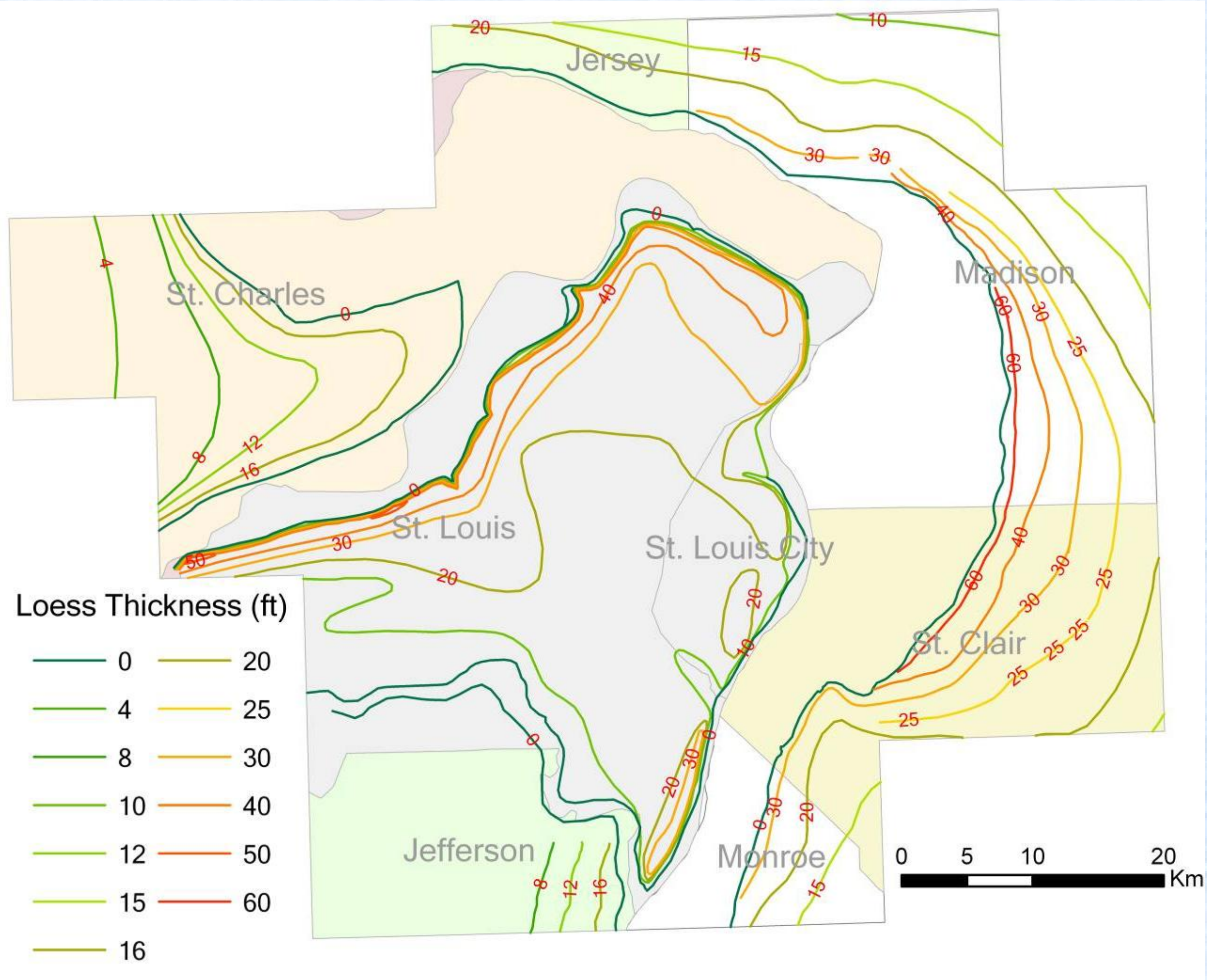
Vector data model

Loess Thickness Map (in feet)

- **Loess (Peoria and Roxana Silts):**

- **Thickest** along the river bluffs bordering the Missouri and Mississippi Rivers; and

- **Thins** exponentially, away from the river bluffs



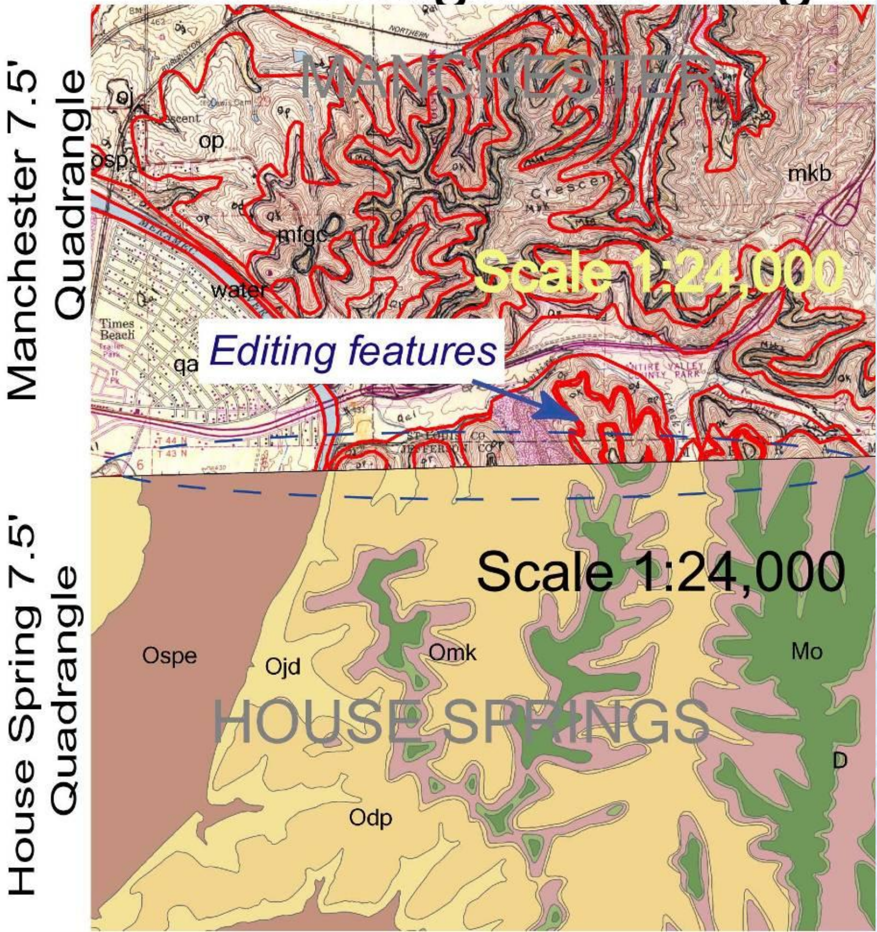
Vector data model

Map Scale Matching Problems

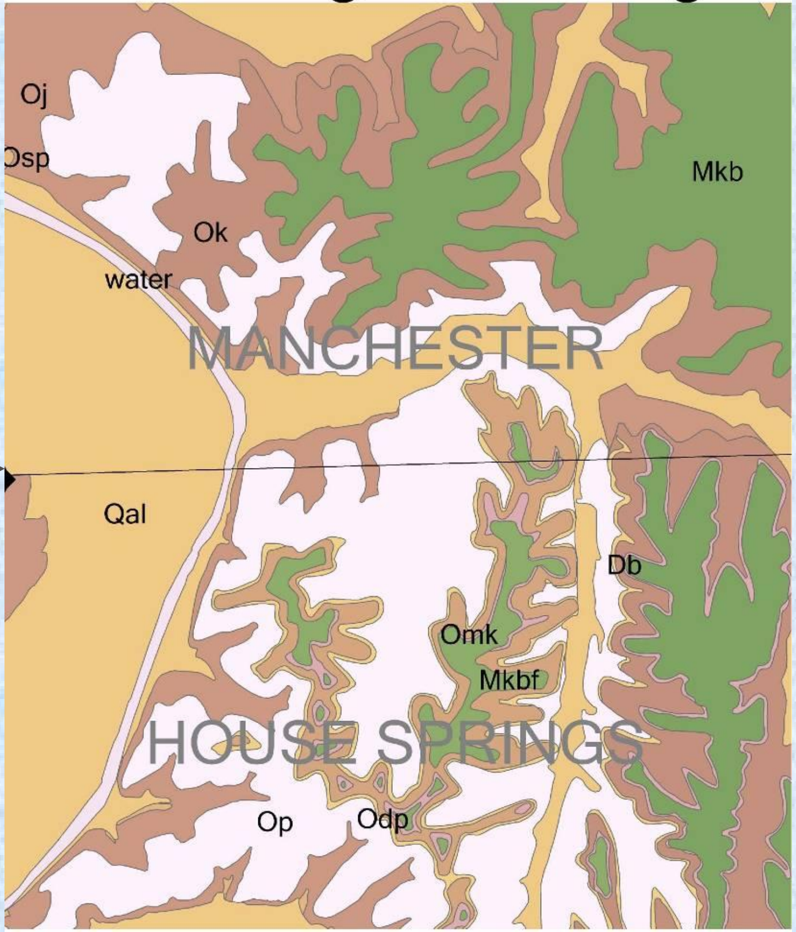
Possible Solutions:

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

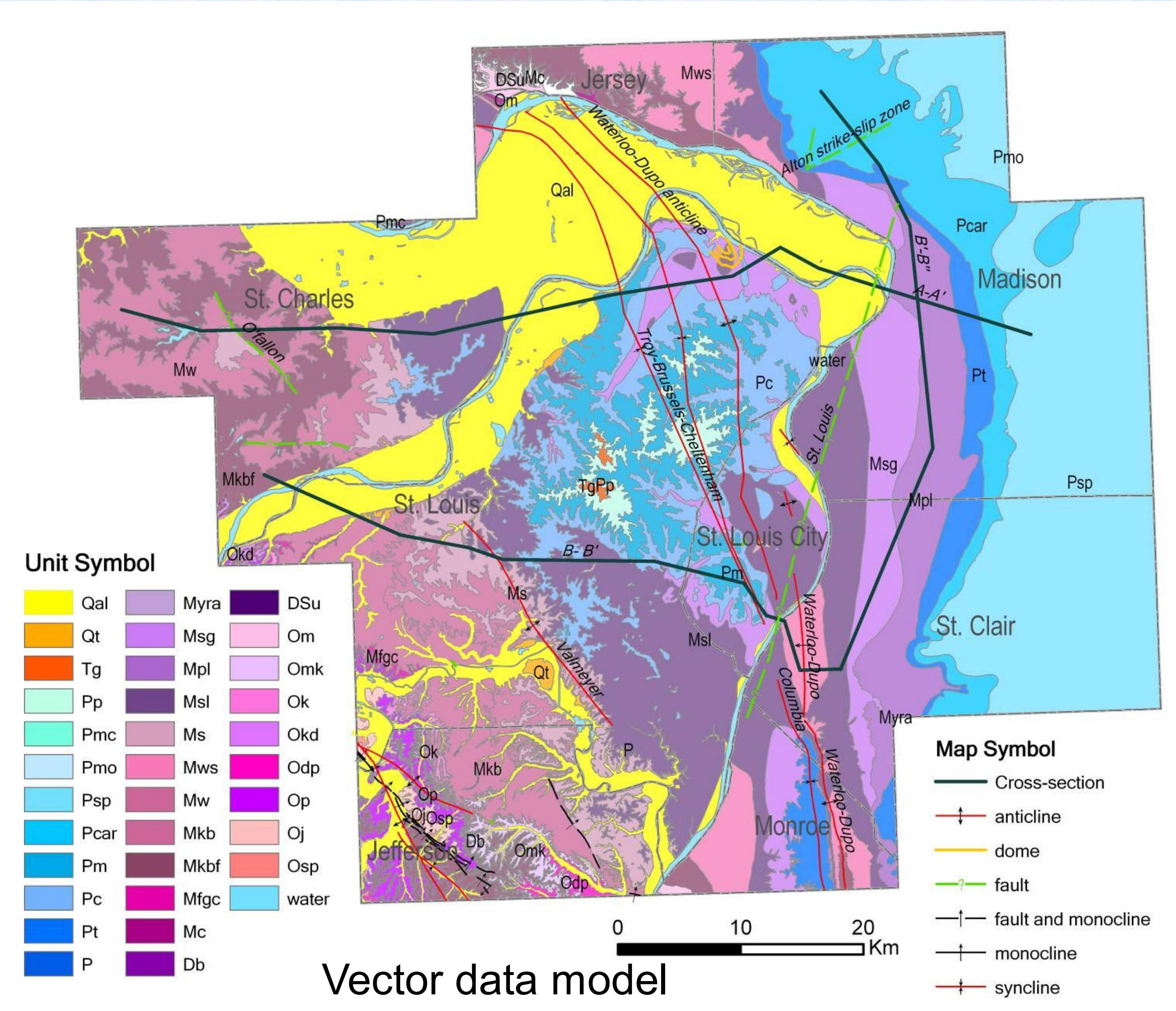
Before edge-matching



After edge-matching



Compiled Bedrock Geology Map

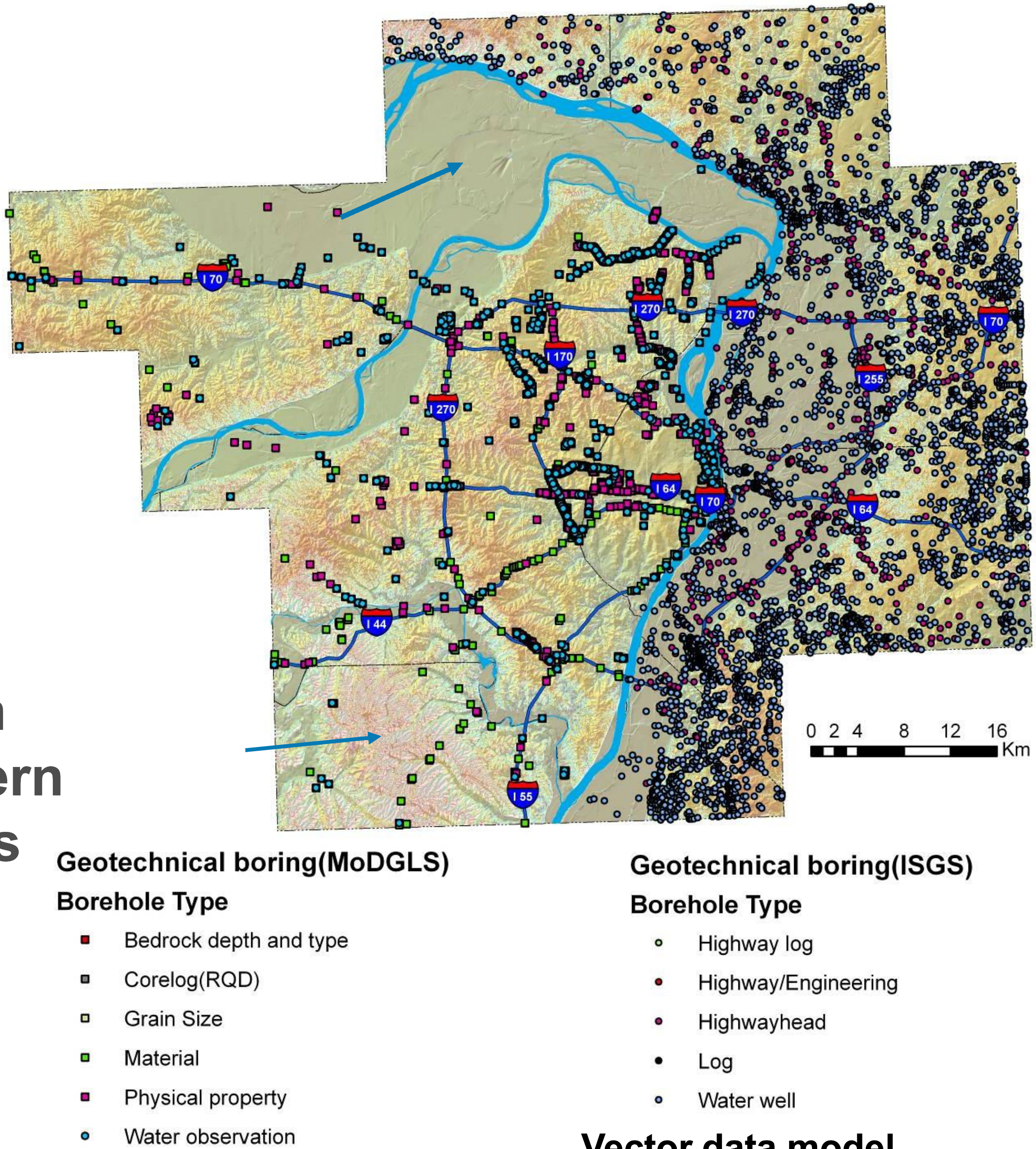


Vector data model

Borehole Locations

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

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



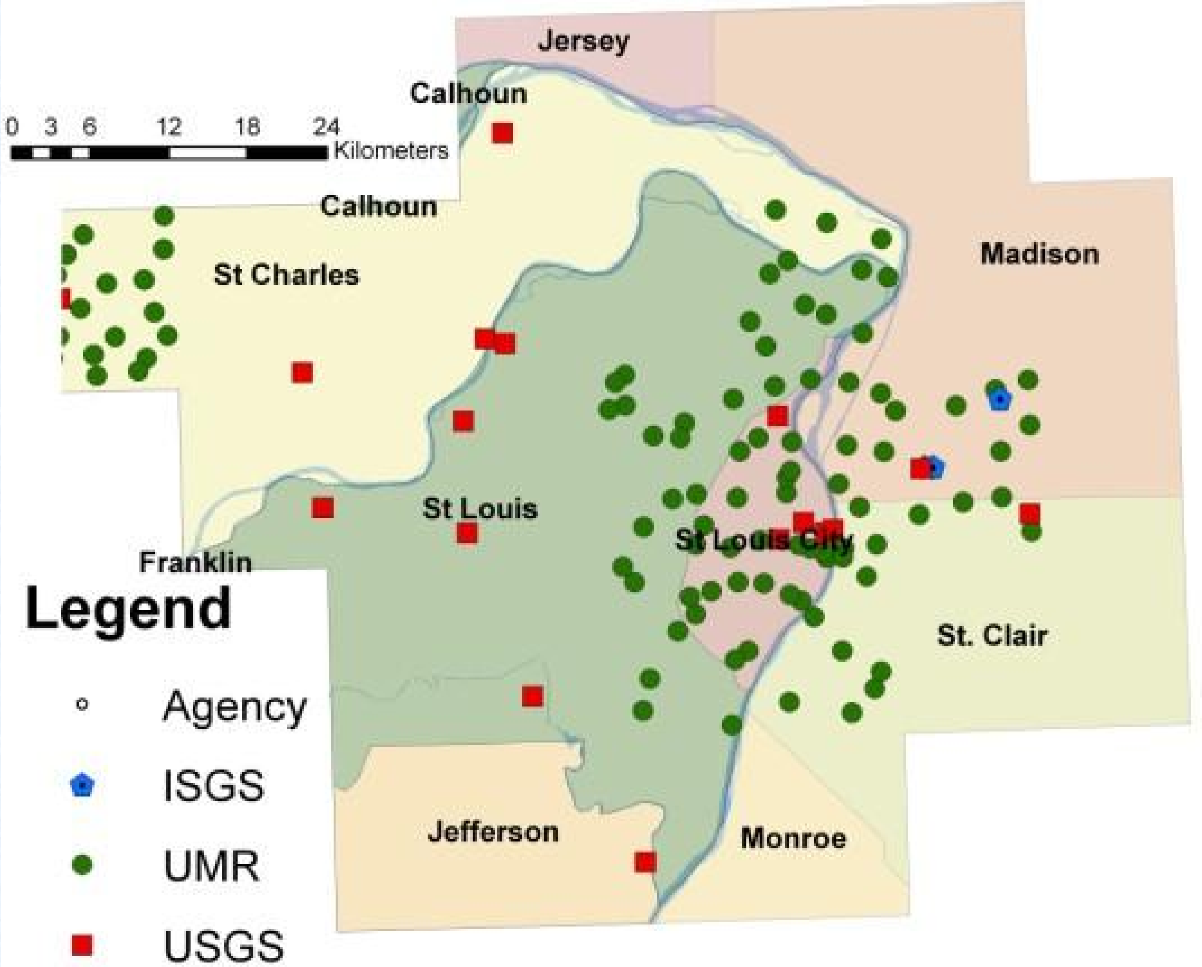
Vector data model

Borehole Information

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

State	Borehole type	Number of records	Item
Missouri	Bedrock	2338	Depth to bedrock, Bedrock type
	Corelog	729	Core recovery (%), Rock Quality Designation (RQD)
	Grain Size	93	Grain size anaysis of soil
	Material	2330	Description of soil material
	Physical Property	1906	Standard Penetration Test (SPT) N-value, Cone Penetration Test (CPT), ASTM class, Unit weight (water content,%), Liquid limits, and Plastic index
	Water Observation	961	Depth to groundwater
	Site	2394	
Illinois	Highway Log	857	Description of soil material
	Highway Engineering	496	Standard Penetration Test (SPT) N-value
	Highway Head	2226	Description of geotechnical boring
	Log	3636	Description of soil material
	Water Well	4728	Description of water well
	Site	4817	

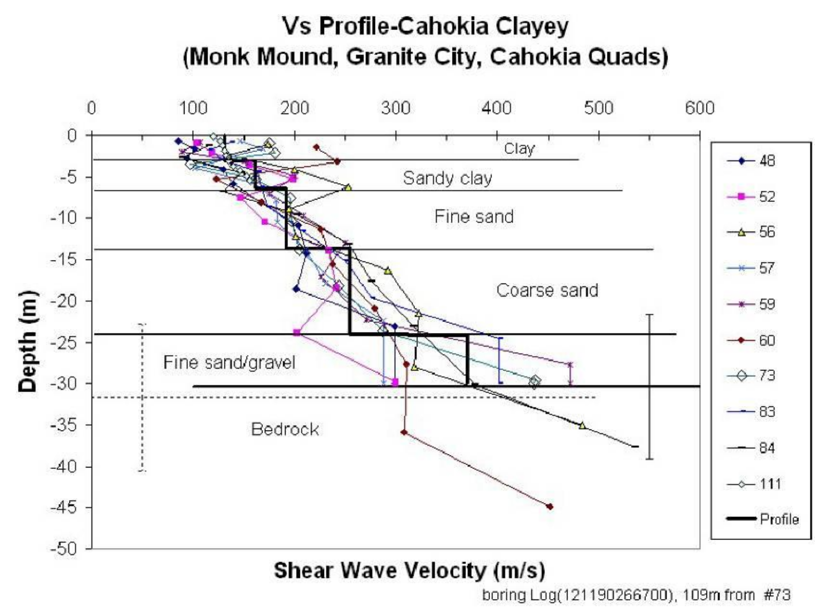
Locations of Shear Wave Velocity (Vs) Measurements



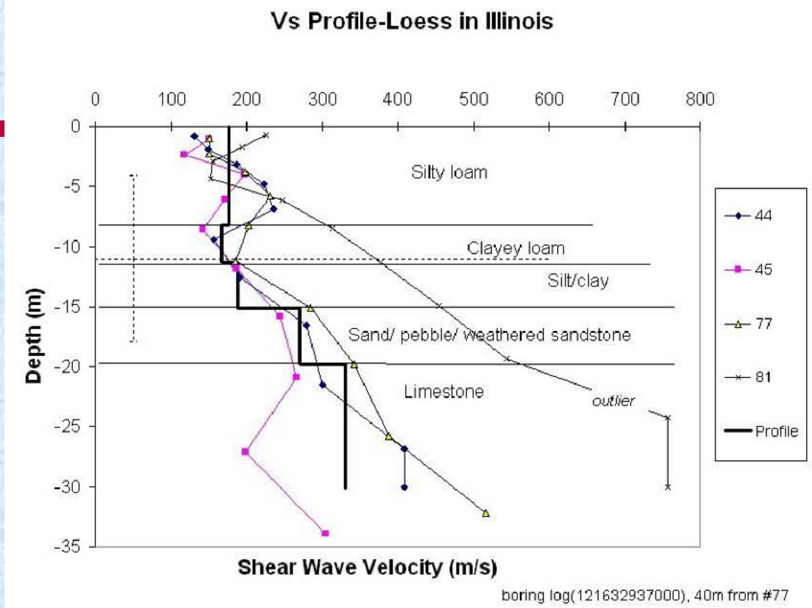
Data Sources (119):

- **ISGS (3)**
- **UMR (99)**
- **USGS (17)**
- **More being added to the database from private sector consultants**

Vs Reference Profiles and Soil Columns derived from adjacent boreholes

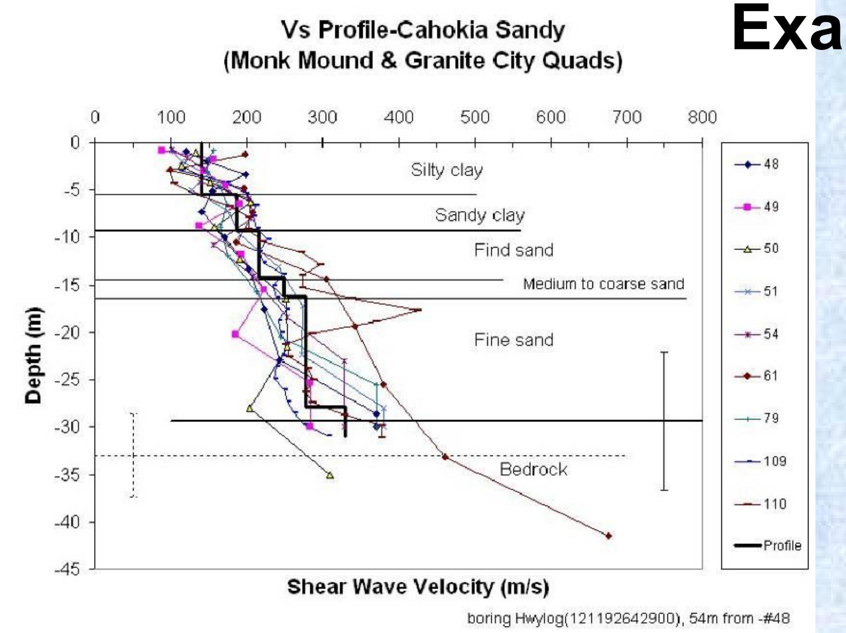

Vs Profile-Cahokia Clayey
(Monk Mound, Granite City, Cahokia Quads)

boring Log(121190266700), 109m from #73

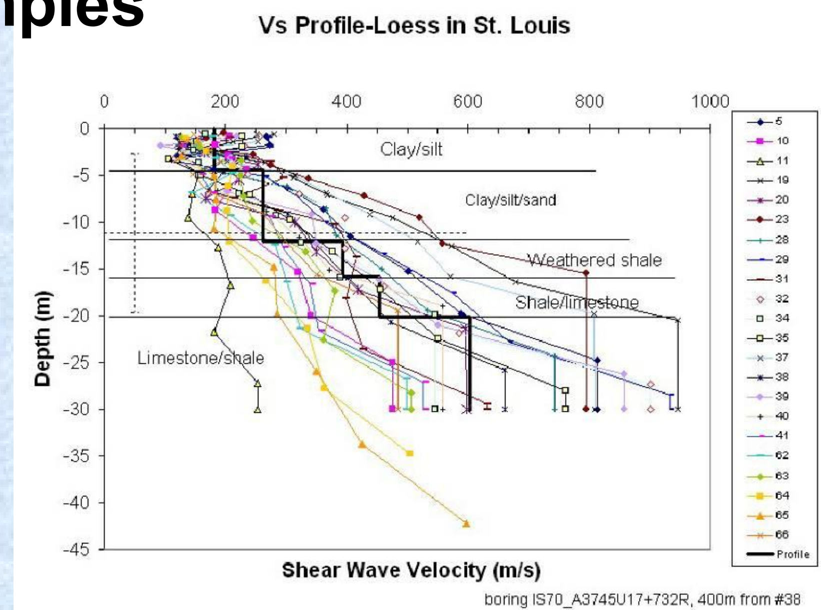

Vs Profile-Loess in Illinois

boring log(121632937000), 40m from #77

Examples


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

boring Hwylog(121192642900), 54m from -#48


Vs Profile-Loess in St. Louis

boring IS70_A3745U17+732R, 400m from #38

Geospatial Prediction of the Groundwater Table

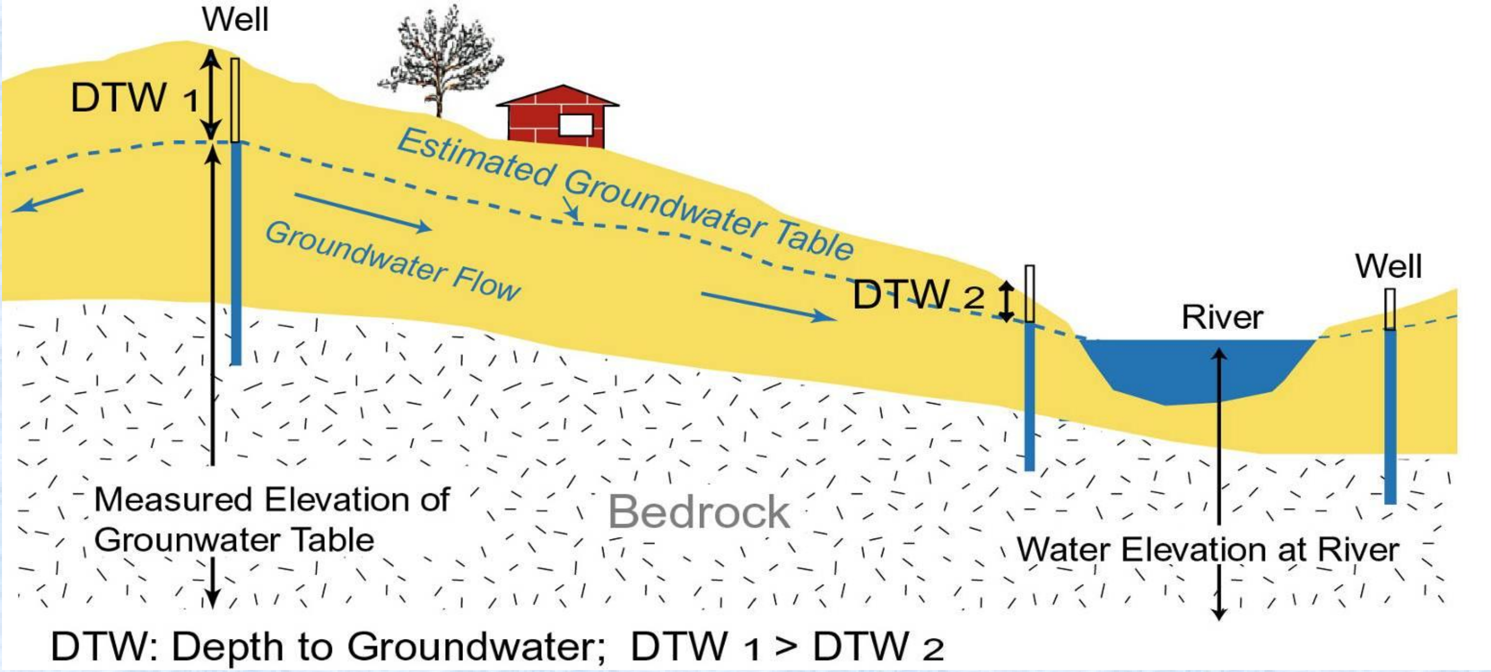
Application: important consideration in engineering and environmental decision making; for

- waste disposal sites
- natural hazards, such as shaking-induced soil liquefaction, and lateral spreads.

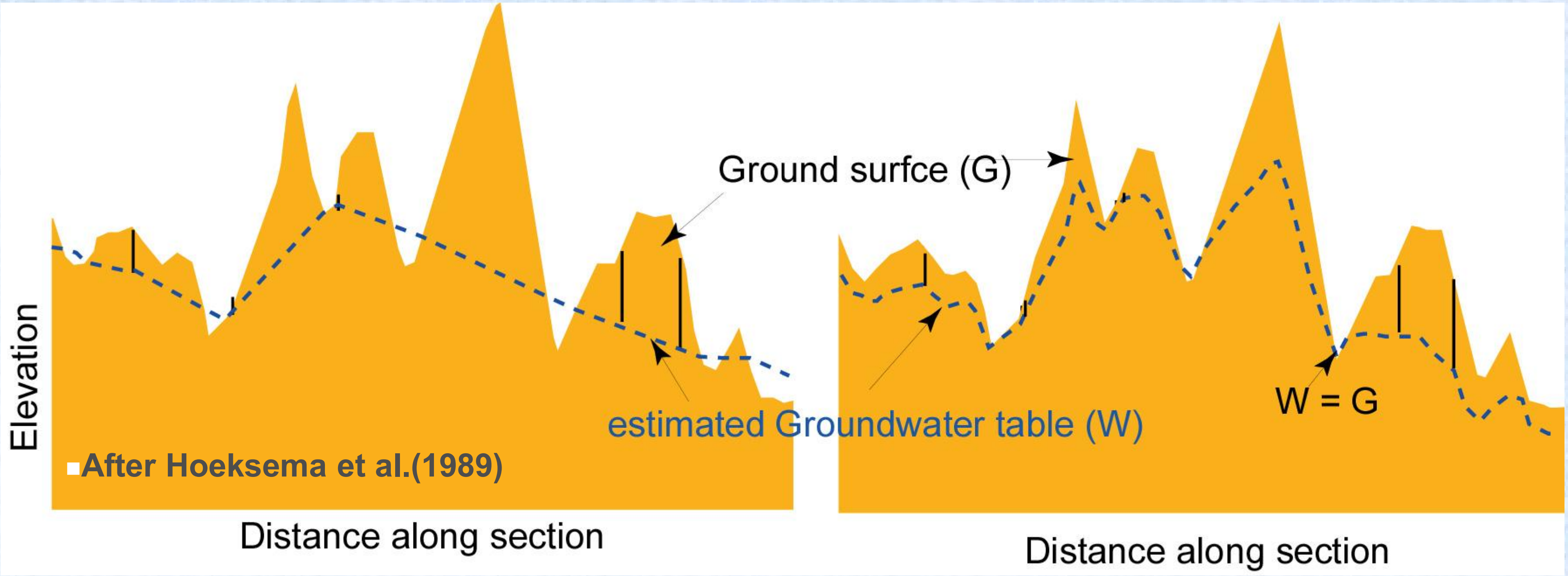
General Specifications of the Groundwater Table

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**



Profile of Groundwater Table (W) with and without considering the ground surface (G)



- After Hoeksema et al.(1989)

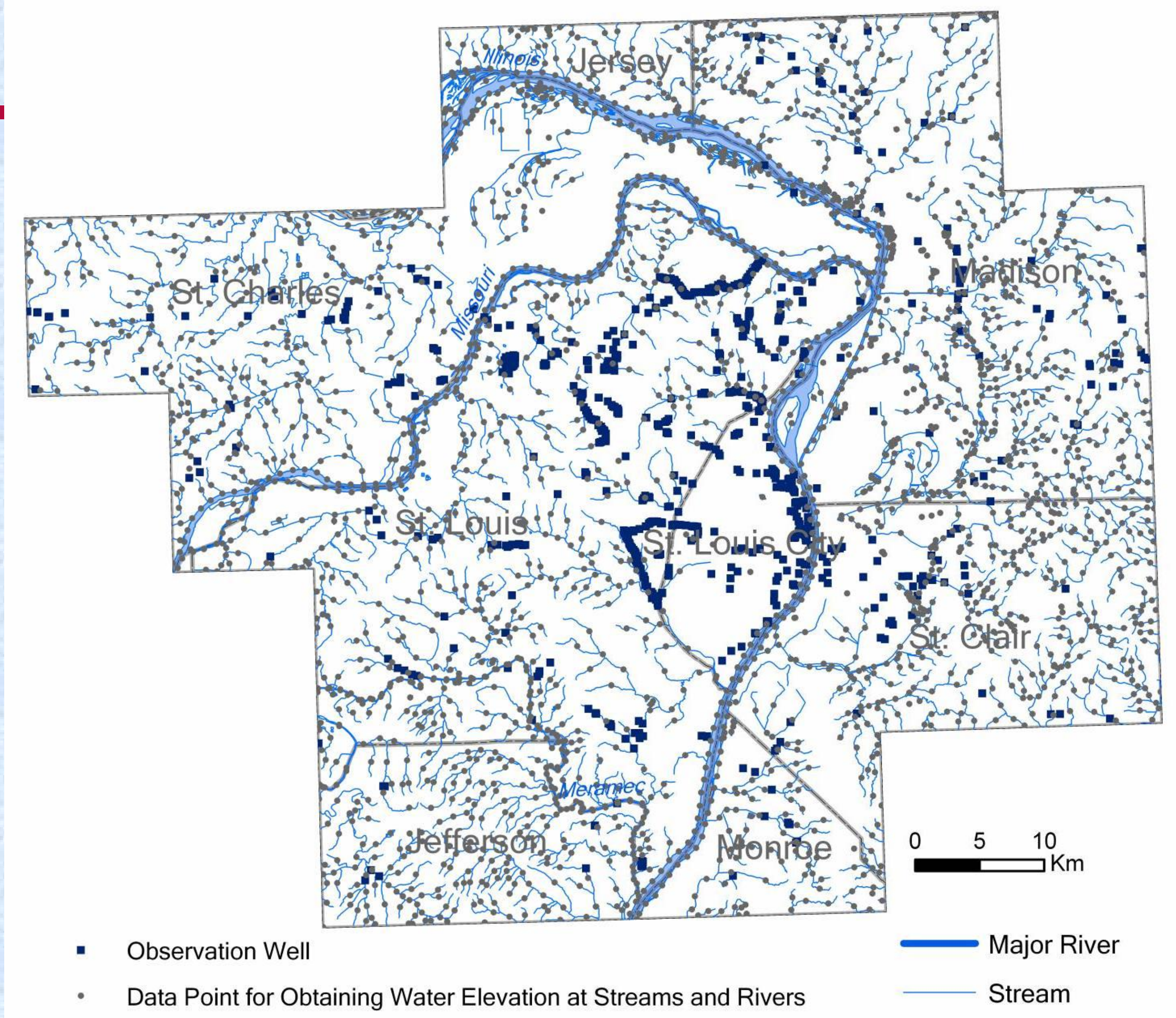
Estimated W without considering G

- Estimate W concerning G and constraining W=G

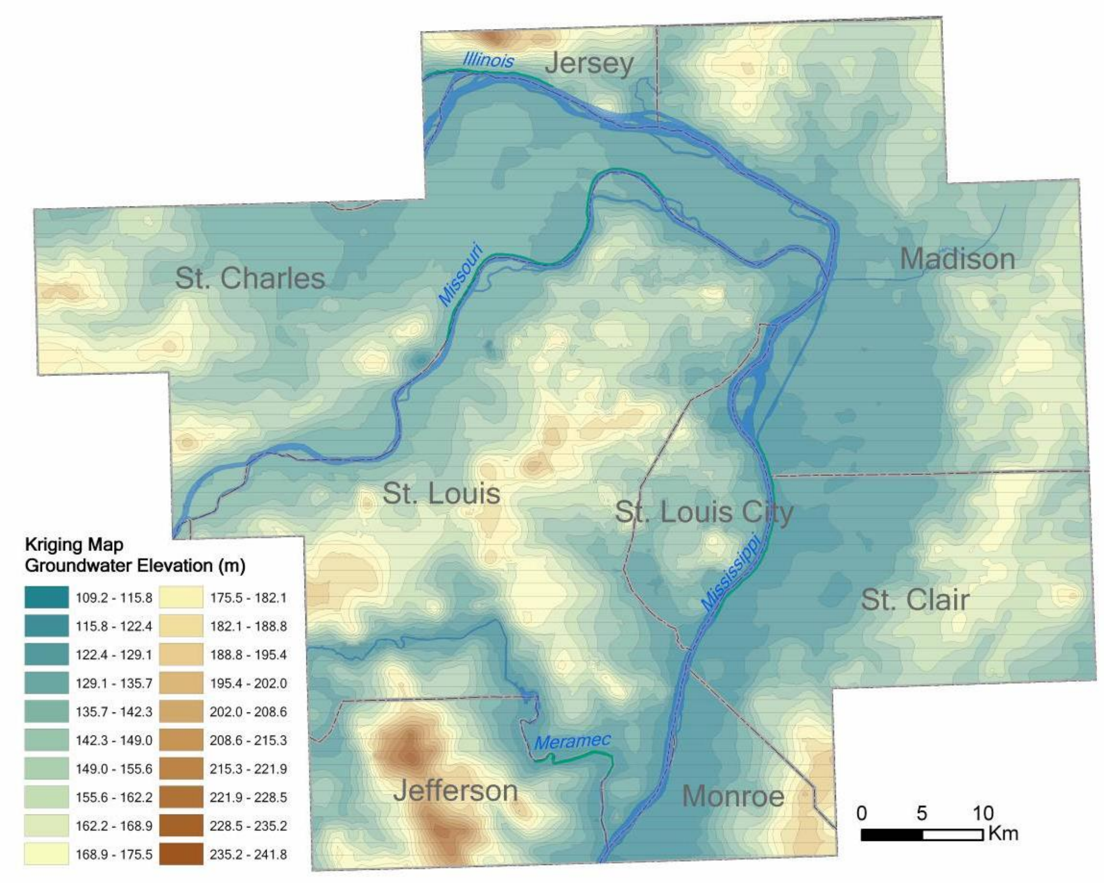
- Using kriging

- Using cokriging

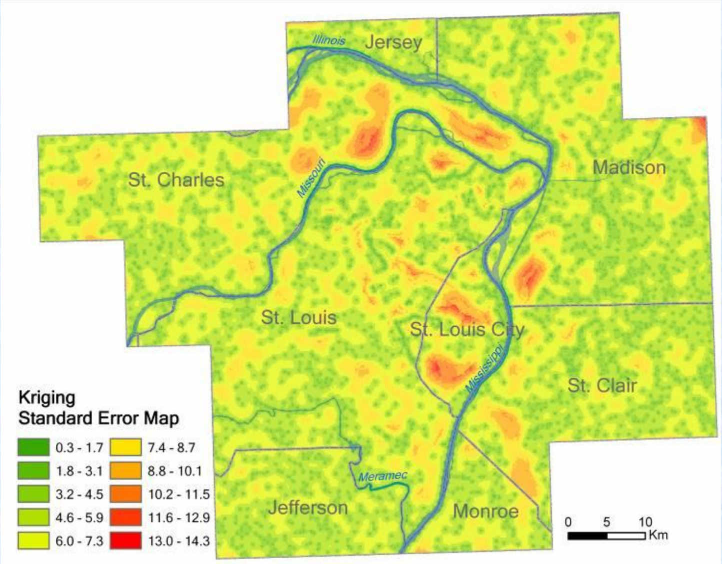
Input data for Modeling Groundwater Table



Kriging Map of Predicted Groundwater Table Elevation



Standard Error Map Using Kriging



- **Raster data model**

Cokriging Map of Groundwater Table

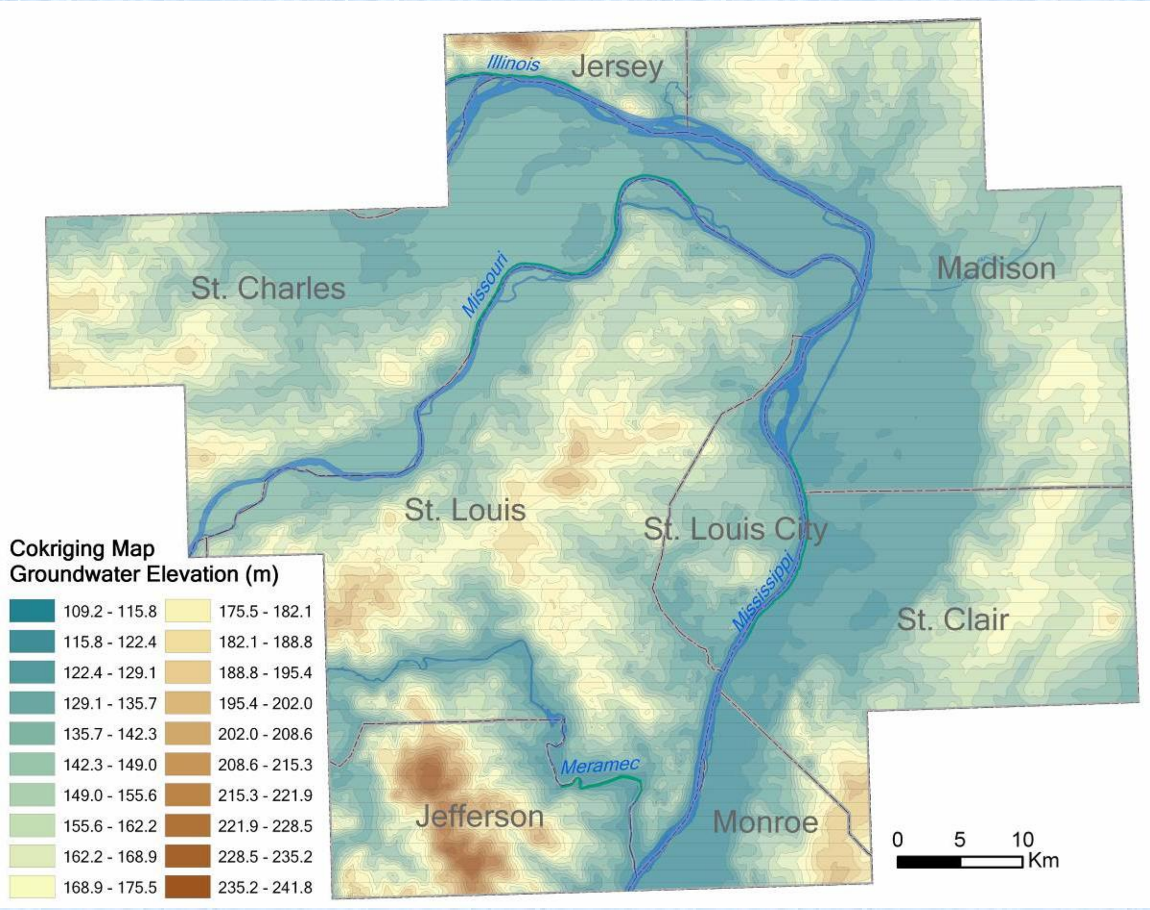
Primary variables:

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

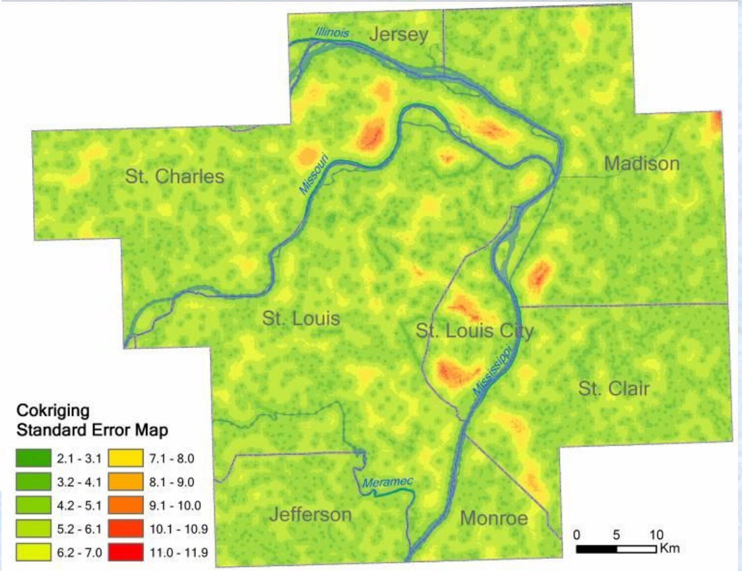
Secondary variables:

- Resolution/accuracy of actual ground elevations (500m × 500m grids), extracted from USGS Digital Elevation Models

2) Cokriging Map of Predicted Groundwater Table



- **Raster data model**

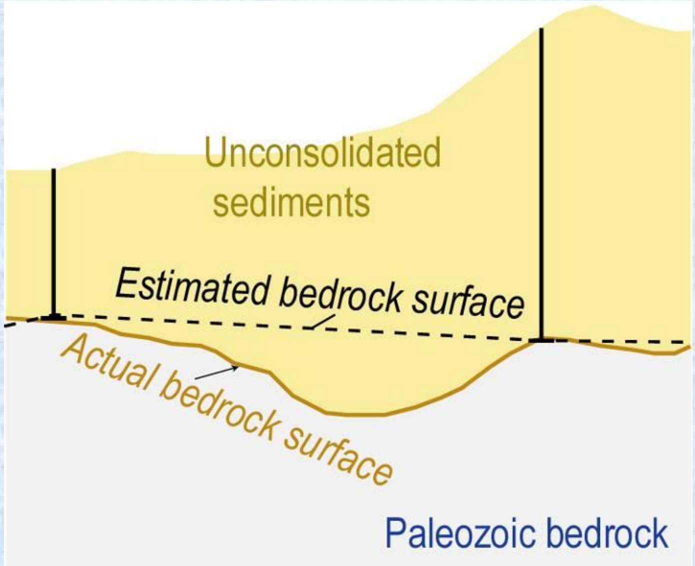


Standard Error Map Using Cokriging

Problems with interpolating the bedrock Surface beneath the ground

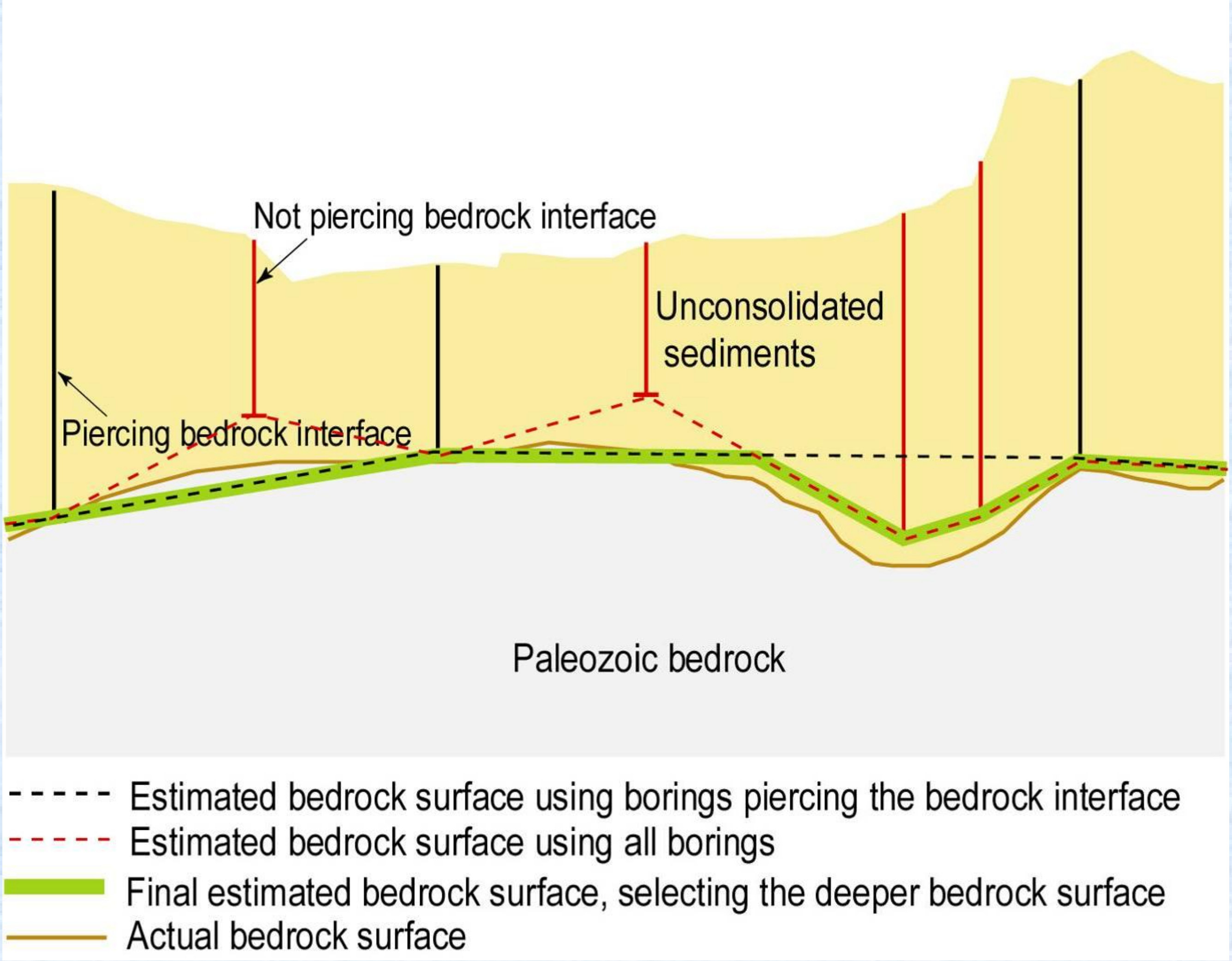
In undulating terrain, the bedrock surface is often a complex, undulating feature, shaped by previous erosional and deformational events

- 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**



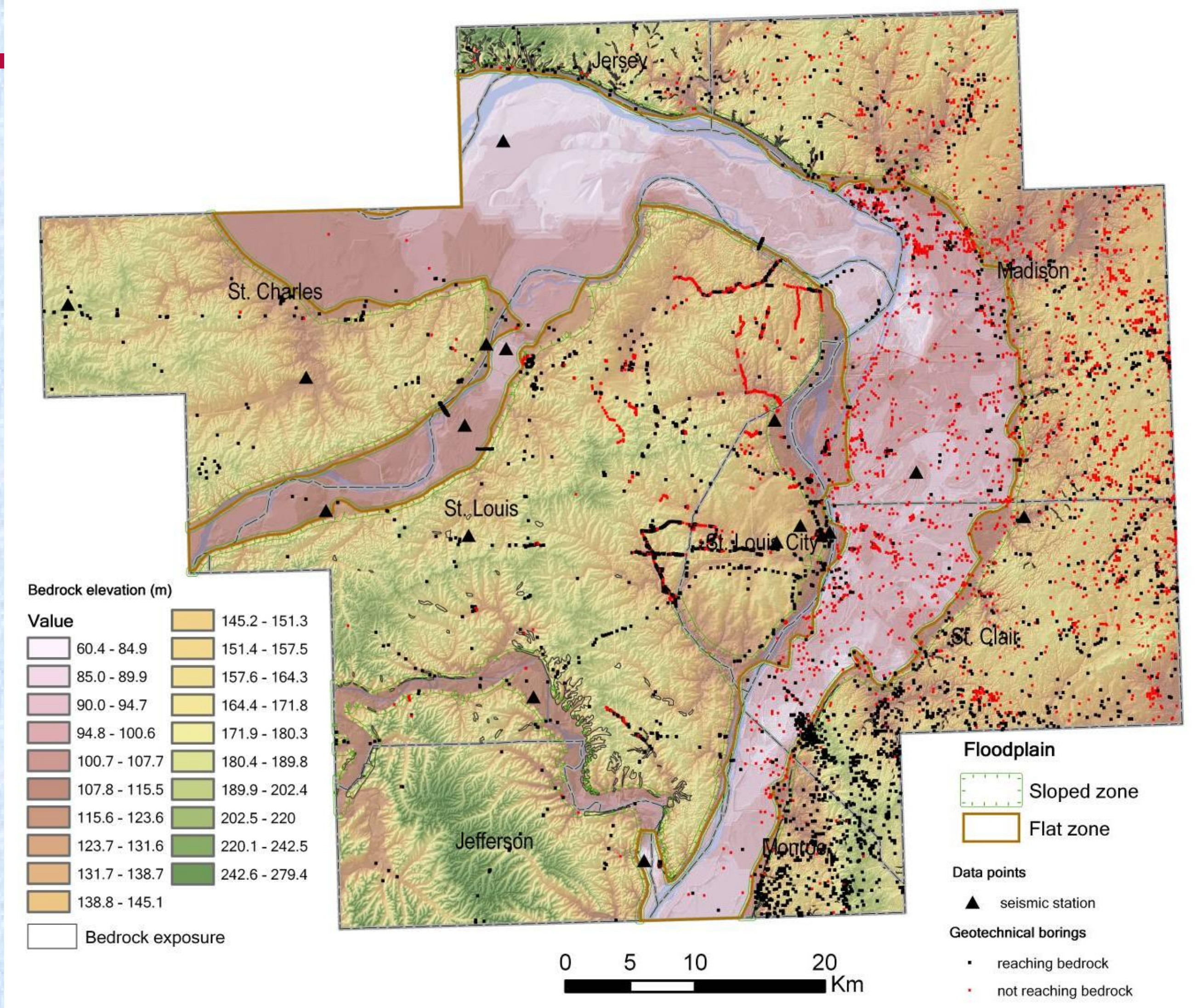
Procedure for Interpolating Depth-to-Bedrock

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



Bedrock elevation (m)

- Raster data model

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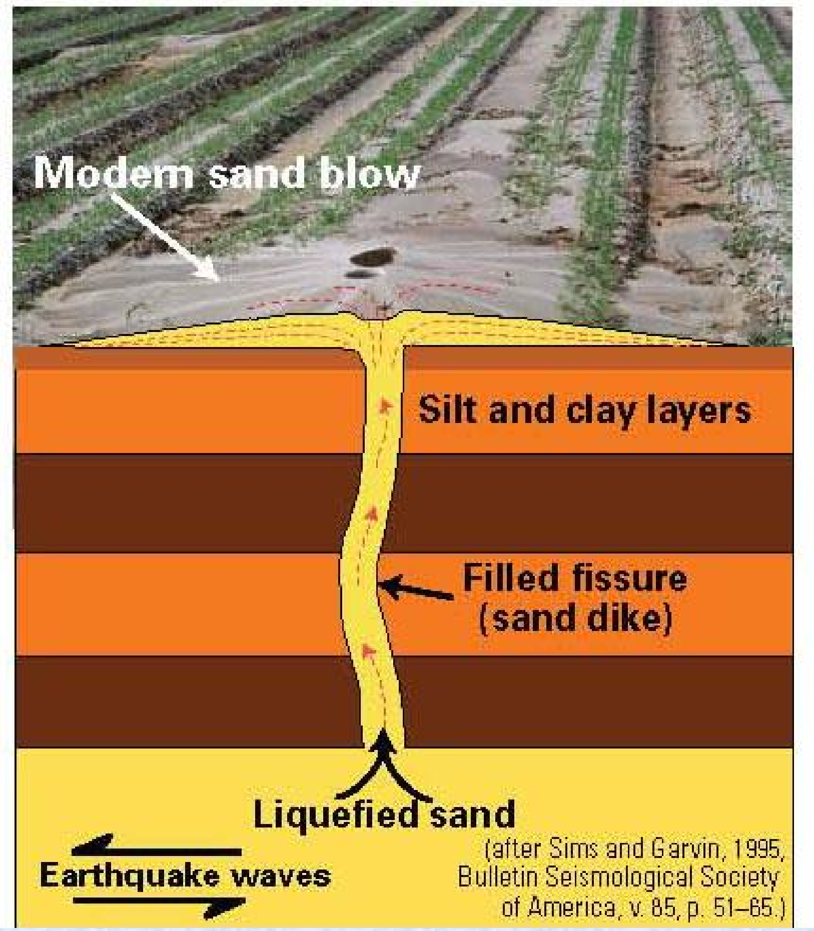
Step 2

Preliminary Assessment of Soil Liquefaction Potential

Liquefaction is a soil failure mechanism that occurs when saturated cohesionless soil looses shear strength. This occurs when the soil pore pressure exceeds the effective confining stress.

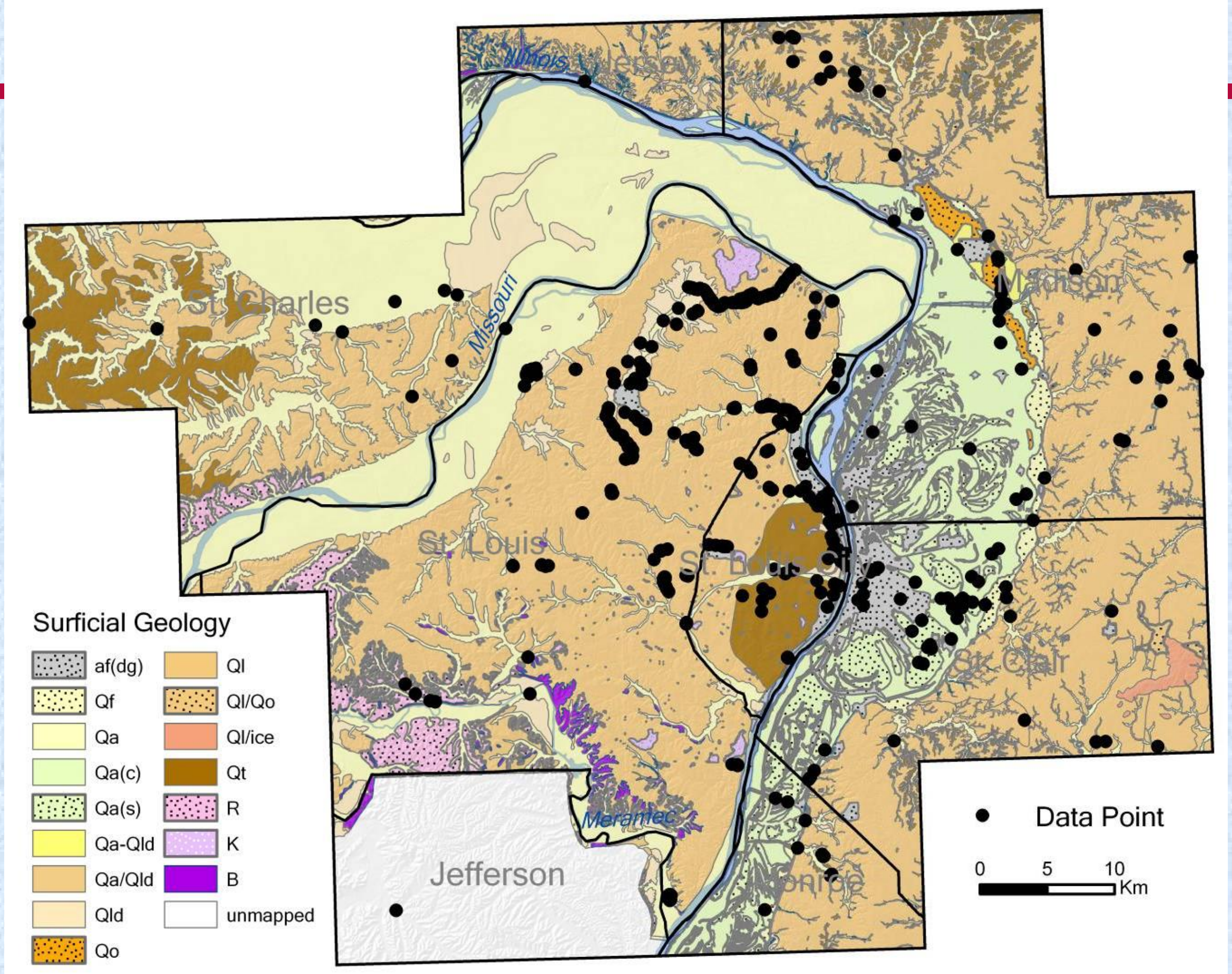
It often occurs in loose unconsolidated sands during earthquake-induced ground shaking, and behaves like a *fluid*.

When the water pressure increases and sand is liquefied, *a slurry of sand/water is forced to the ground surface.*



(after Sims and Garvin, 1995, Bulletin Seismological Society of America, v. 85, p. 51–65.)

Locations of 564 Borings used to calculate the Liquefaction Potential Index, or LPI



- **Data Sources** (Boring information):
  - MoDNR-DGLS, ISGS

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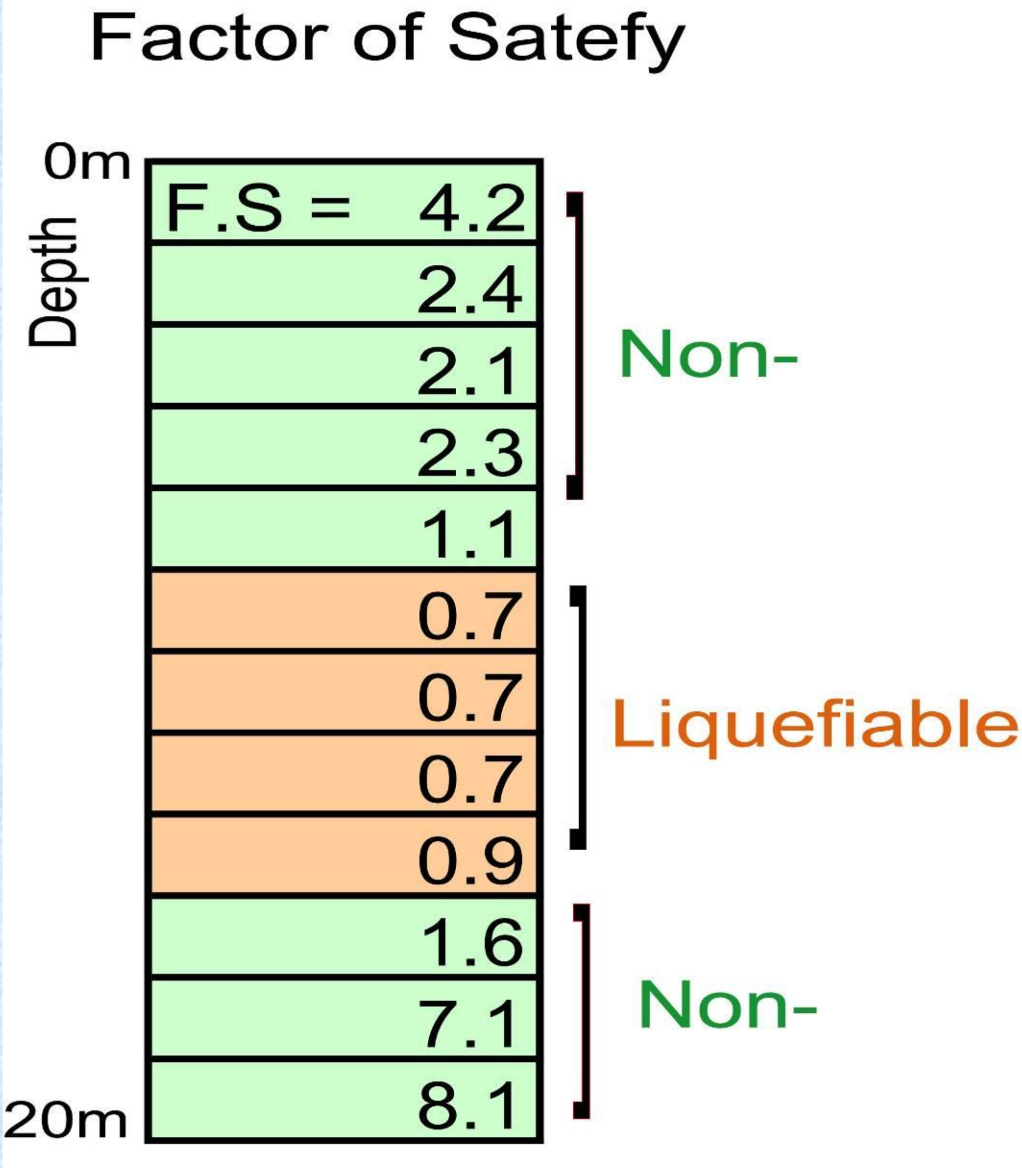
Historical Liquefaction Severity Assessed from LPI (Iwasaki, 1982)

LPI	Severity of Liquefaction
0	None
$0 < LPI \leq 5$	Little to none
$5 < LPI \leq 15$	Moderate
$15 < LPI \leq 100$	Severe

- The LPI technique evaluates the entire soil column overlying the stable bedrock
- The higher the LPI value, the more severe liquefaction damage.

Advantage of LPI method over FS

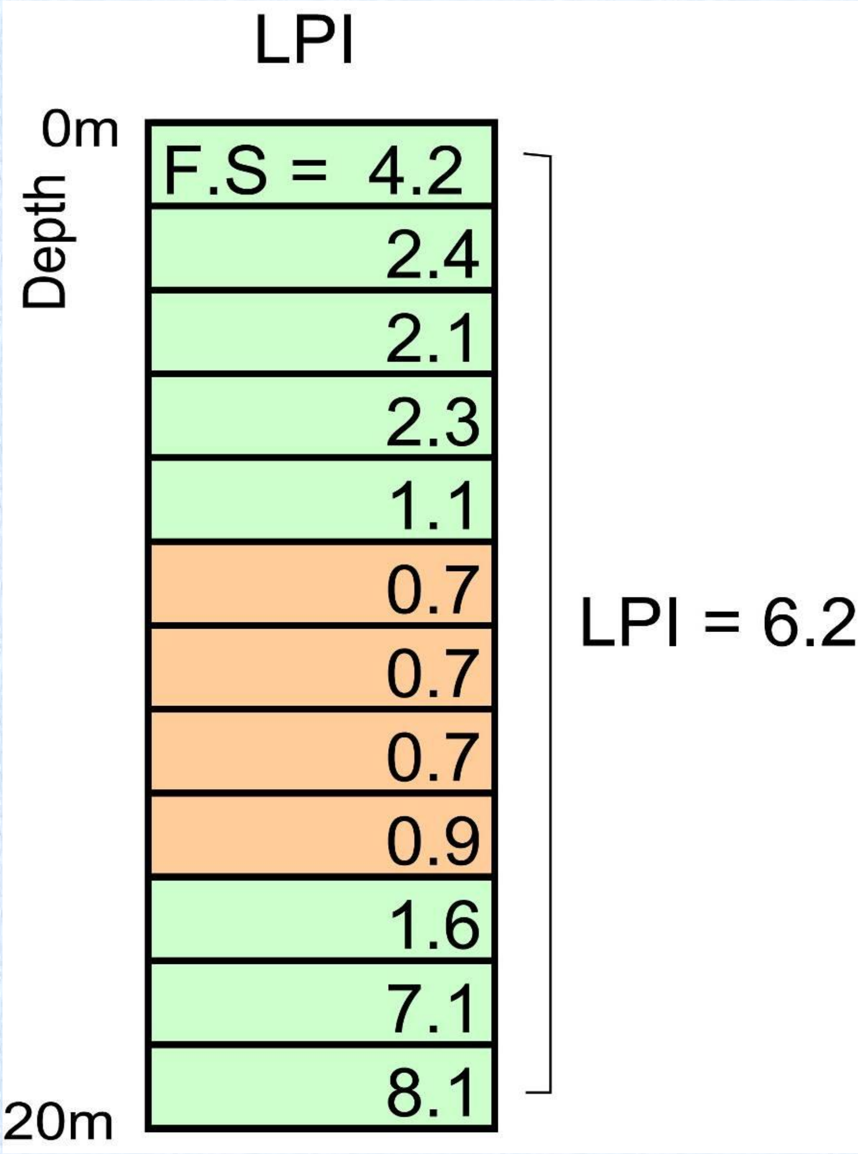


Where the mixture of a liquefiable and non-liquefiable soil layer exists at a single boring,

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

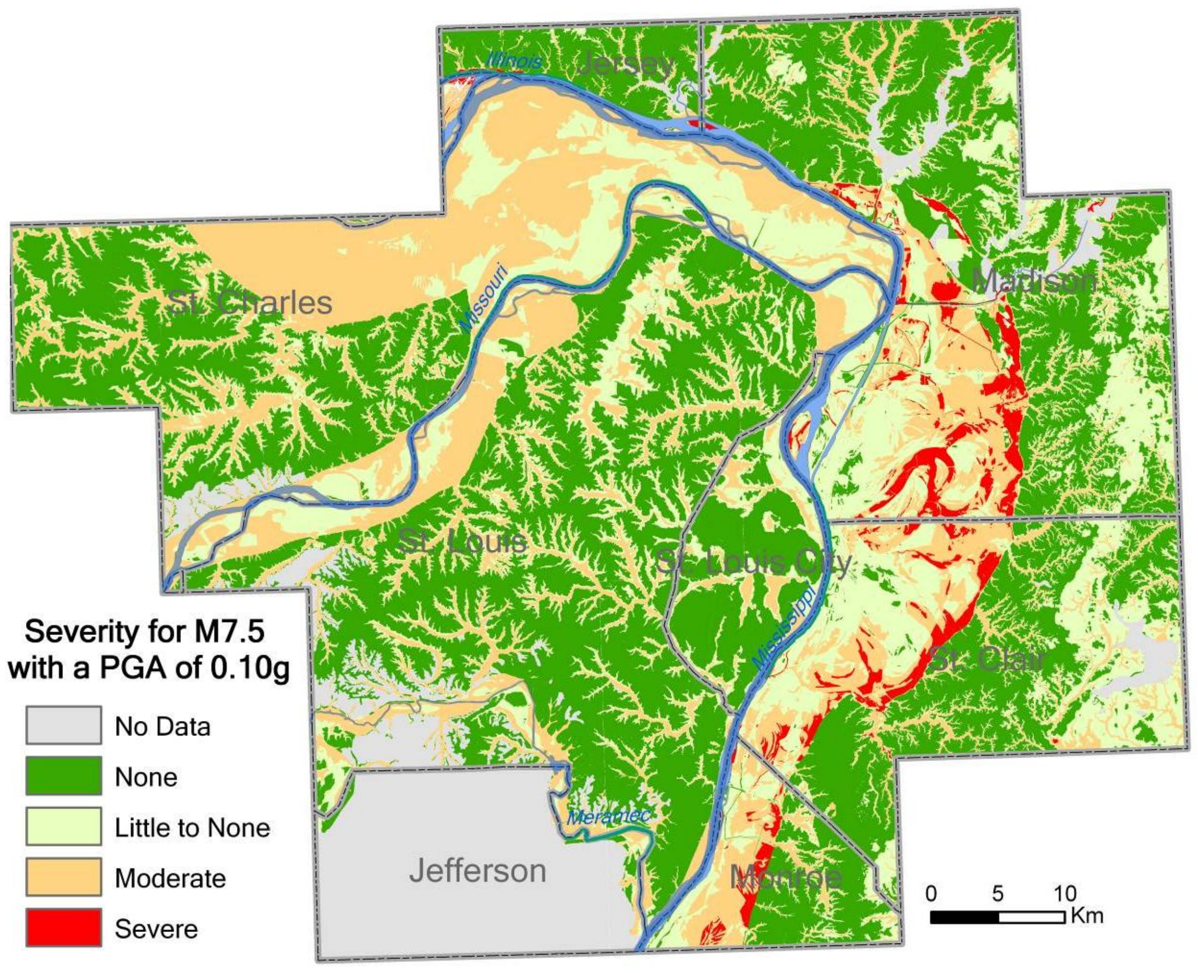
Liquefaction potential in the upper Mississippi Embayment may not be a significant issue at Magnitudes < 6.4 (Obermeier, 1989; Tuttle and Schweig, 1995)

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):

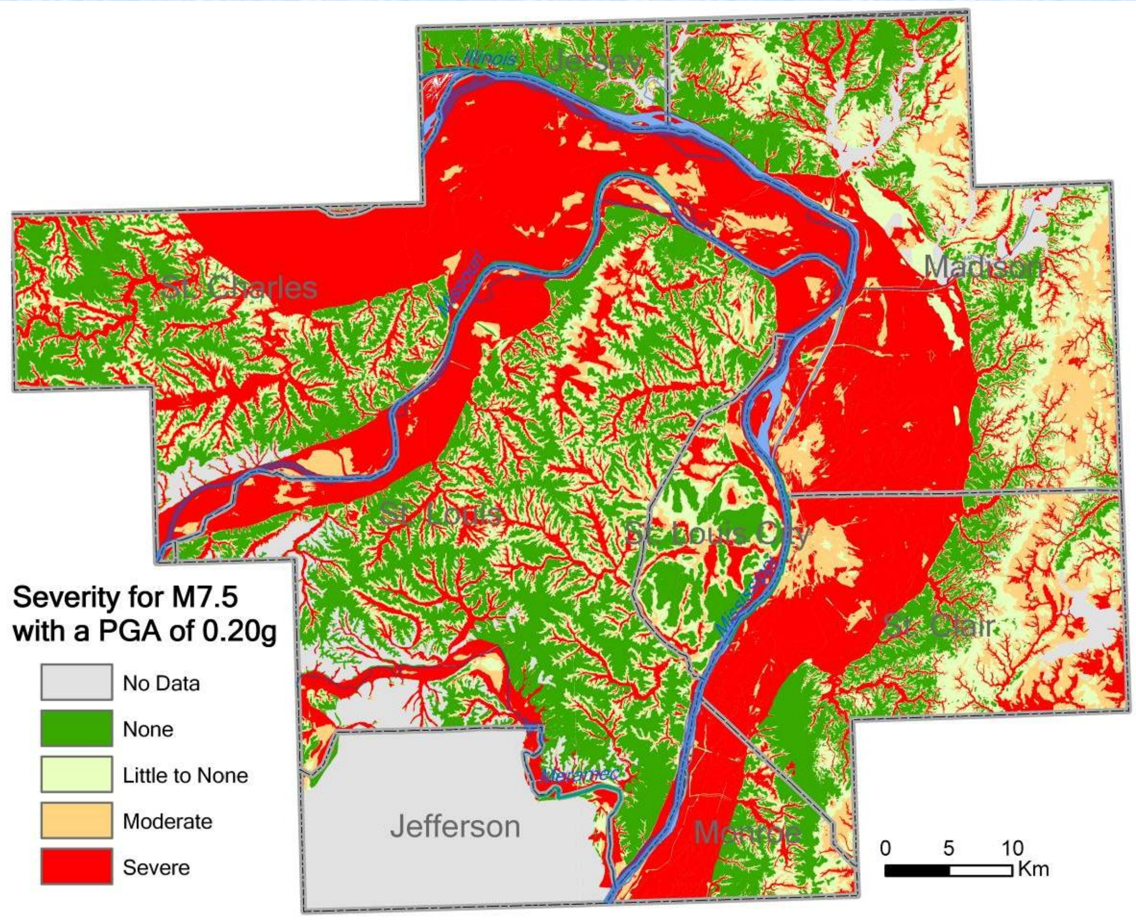
- **Alluvial fans in part (where, gwt<0.5m) in Illinois**
- **Near confluence of Mississippi-Illinois rivers**



Grey areas have insufficient number of borings to analyze

Liquefaction Potential Map (inferred from LPI) for M7.5 with 0.20 PGA

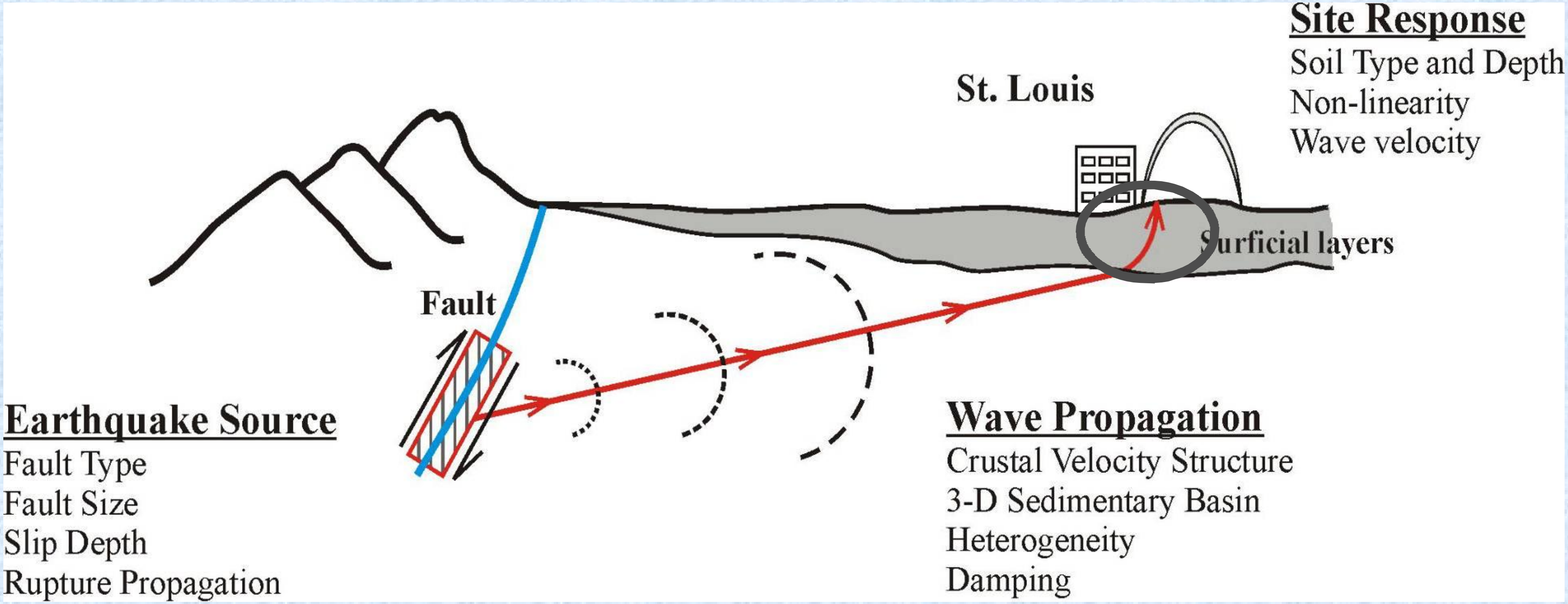
- Severe Liquefaction Potential Area (LPI>15):
  - **Alluvial fan** in part (gwt<4.7m) in Illinois
  - **Alluvium** in part (gwt<4.4m) along major rivers and streams
  - **Clayey alluvium** (gwt<4.6m) and **sandy alluvium** (gwt<5.1m) in ox bow & adjacent alluvial fan



Step 3

Physical Factors Affecting Seismic Site Response

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



Site Response
Soil Type and Depth
Non-linearity
Wave velocity

Earthquake Source
Fault Type
Fault Size
Slip Depth
Rupture Propagation

Wave Propagation
Crustal Velocity Structure
3-D Sedimentary Basin
Heterogeneity
Damping

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) what is experienced by a building, as modeled on a massless vertical rod, having the same natural period of vibration as the building.

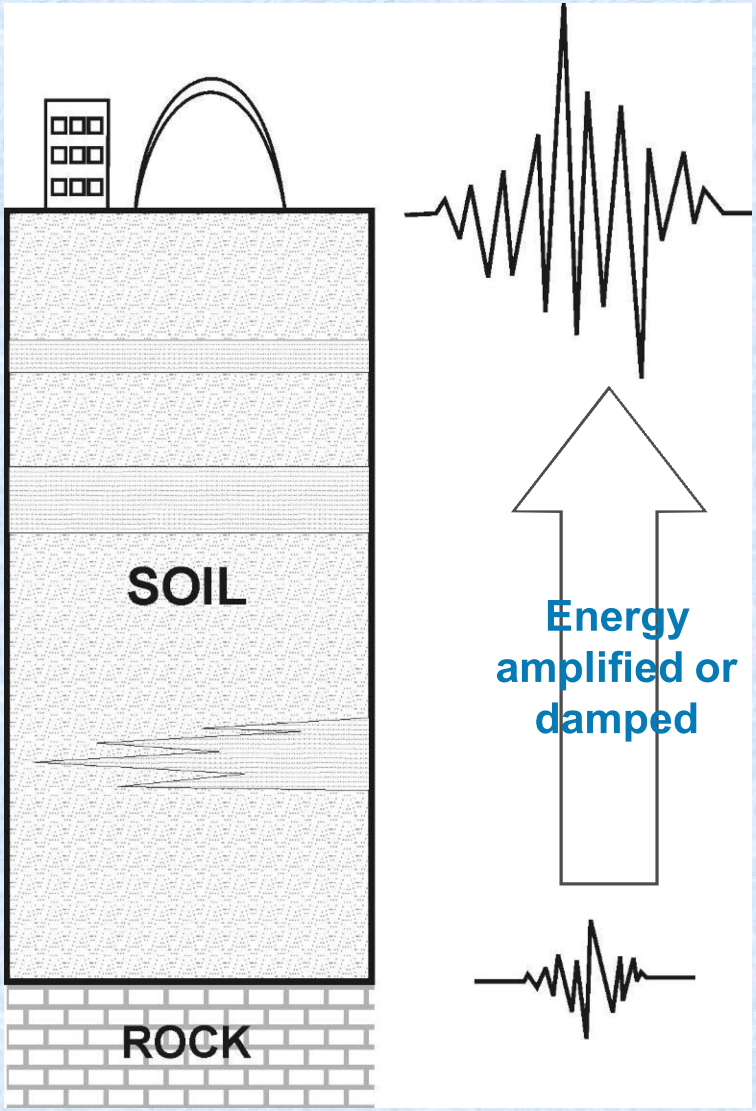
Estimating surface accelerations

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

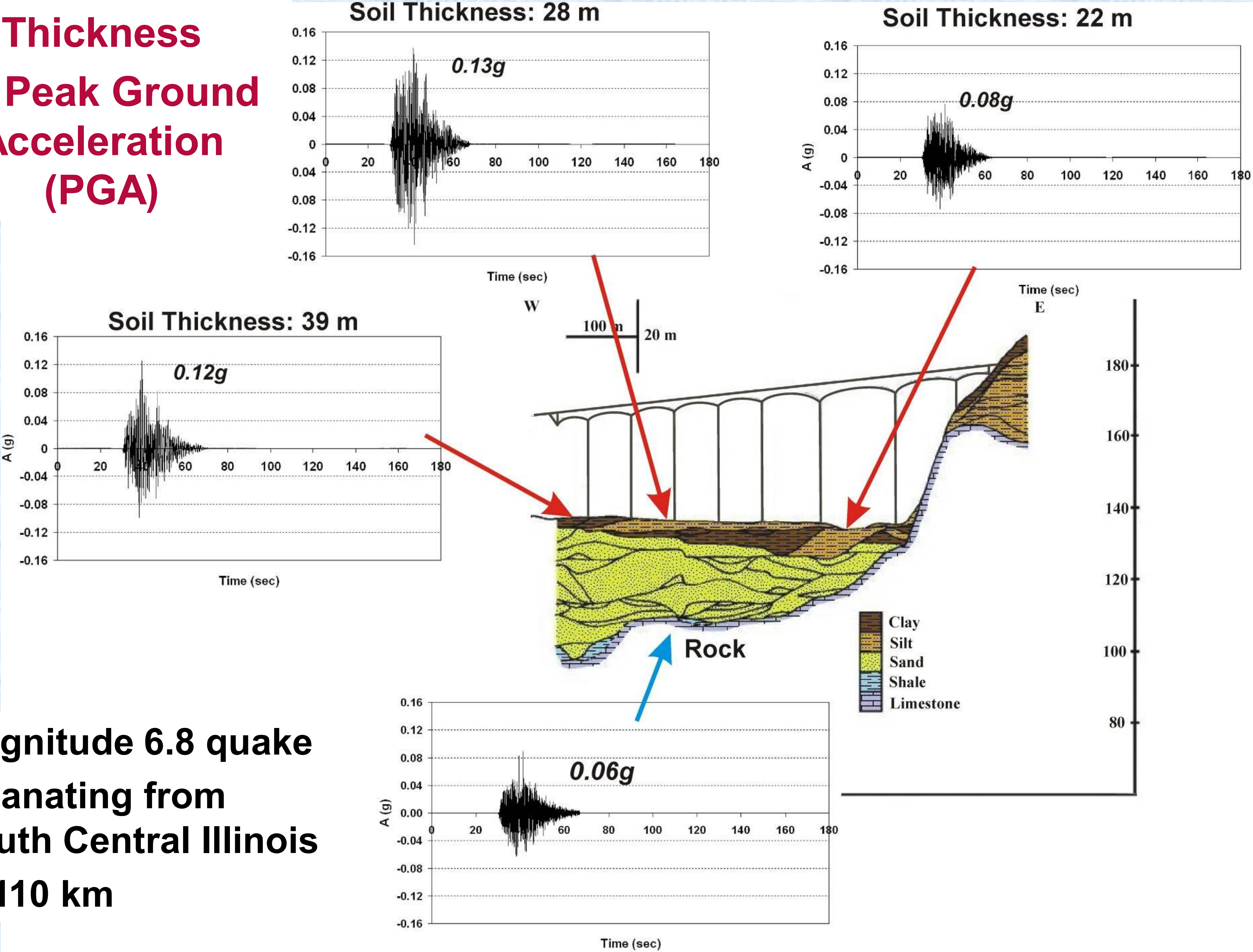
Typical input data includes:

- **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



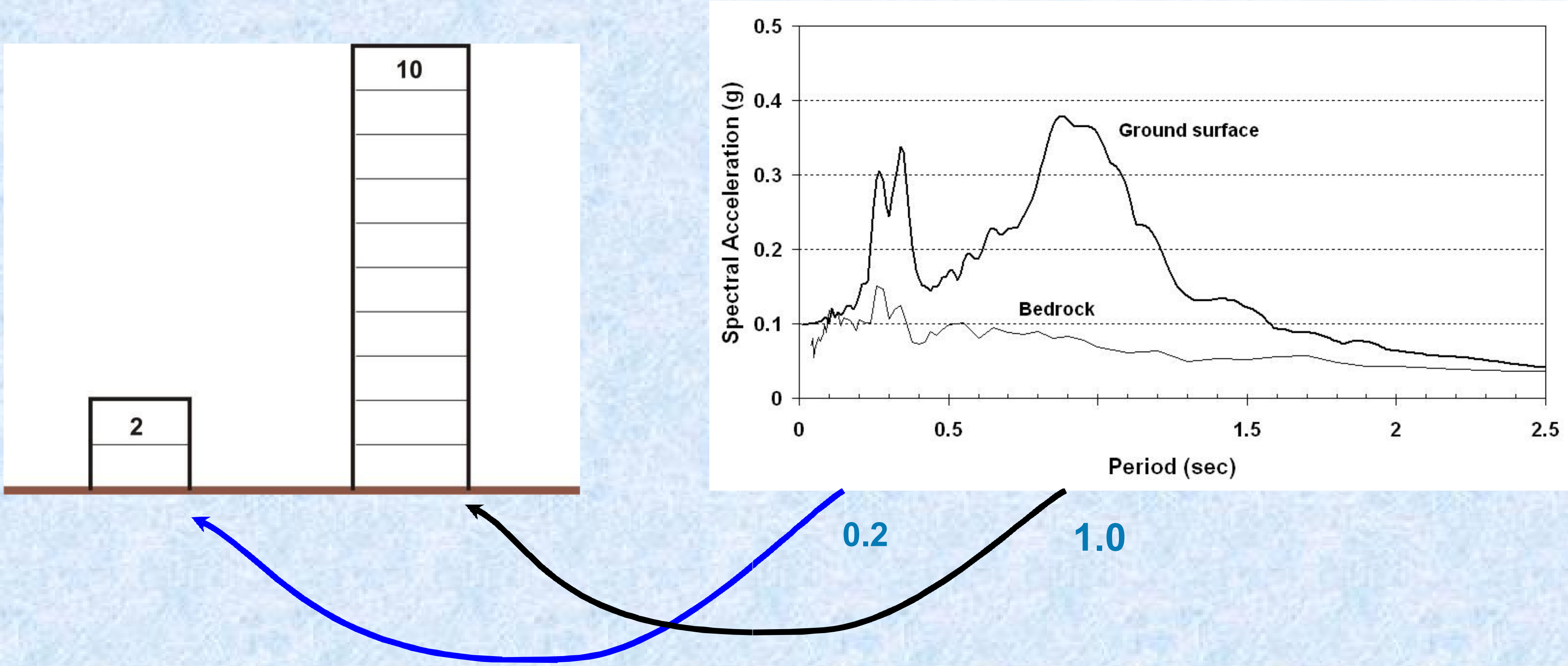
Effect of Soil Thickness on Peak Ground Acceleration (PGA)



Magnitude 6.8 quake emanating from South Central Illinois at 110 km

Spectral Accelerations (SA)

The spectral acceleration value varies with the natural period of the structure.

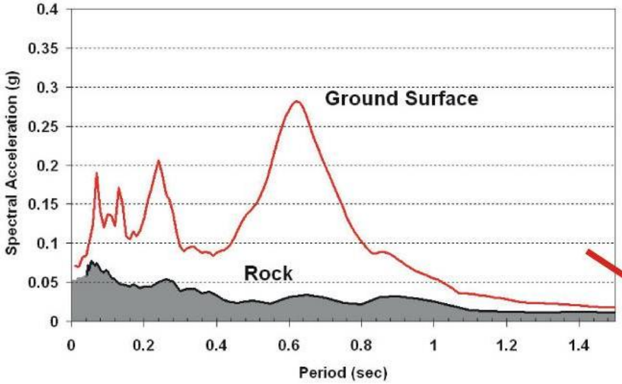


(approximately related)

Effect of Soil Thickness on RESPONSE SPECTRA

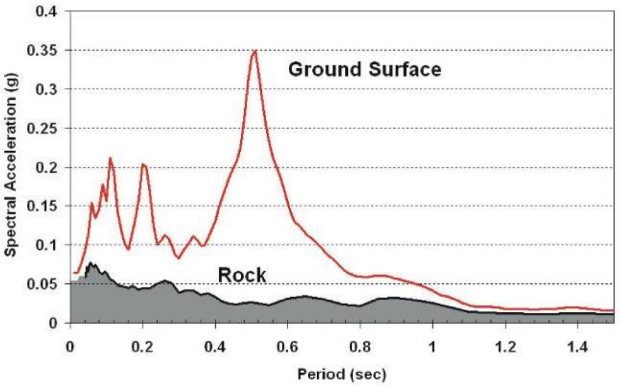
Soil Thickness: 28 m

Peak SA = 0.28 g
Peak Period = 0.62 sec



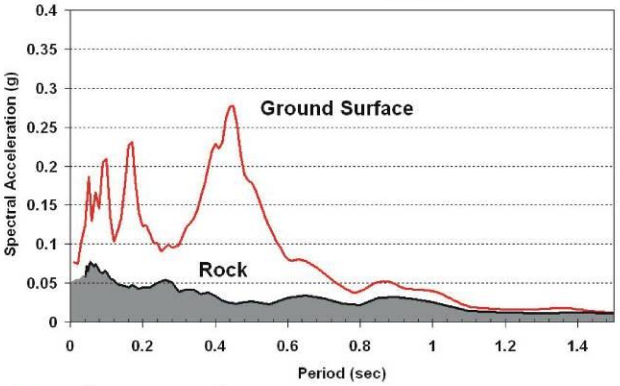
Soil Thickness: 25 m

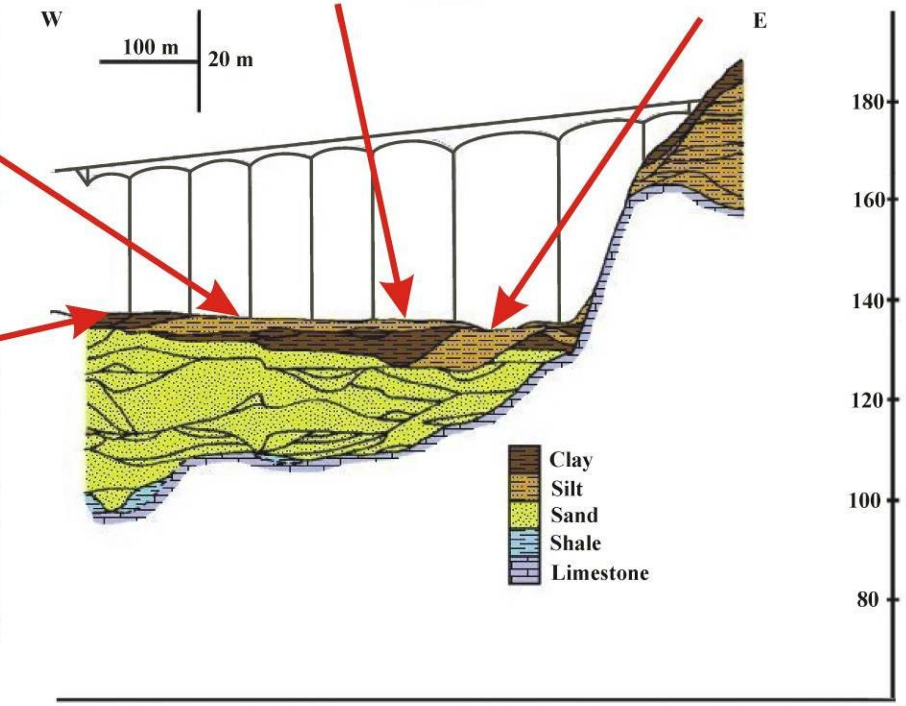
Peak SA = 0.35 g
Peak Period = 0.51 sec

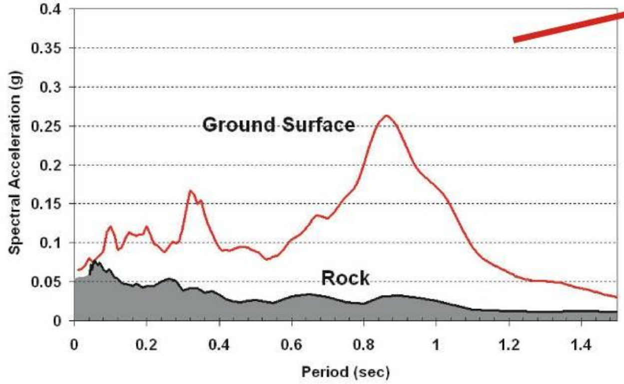


Soil Thickness: 22 m

Peak SA = 0.28 g
Peak Period = 0.45 sec

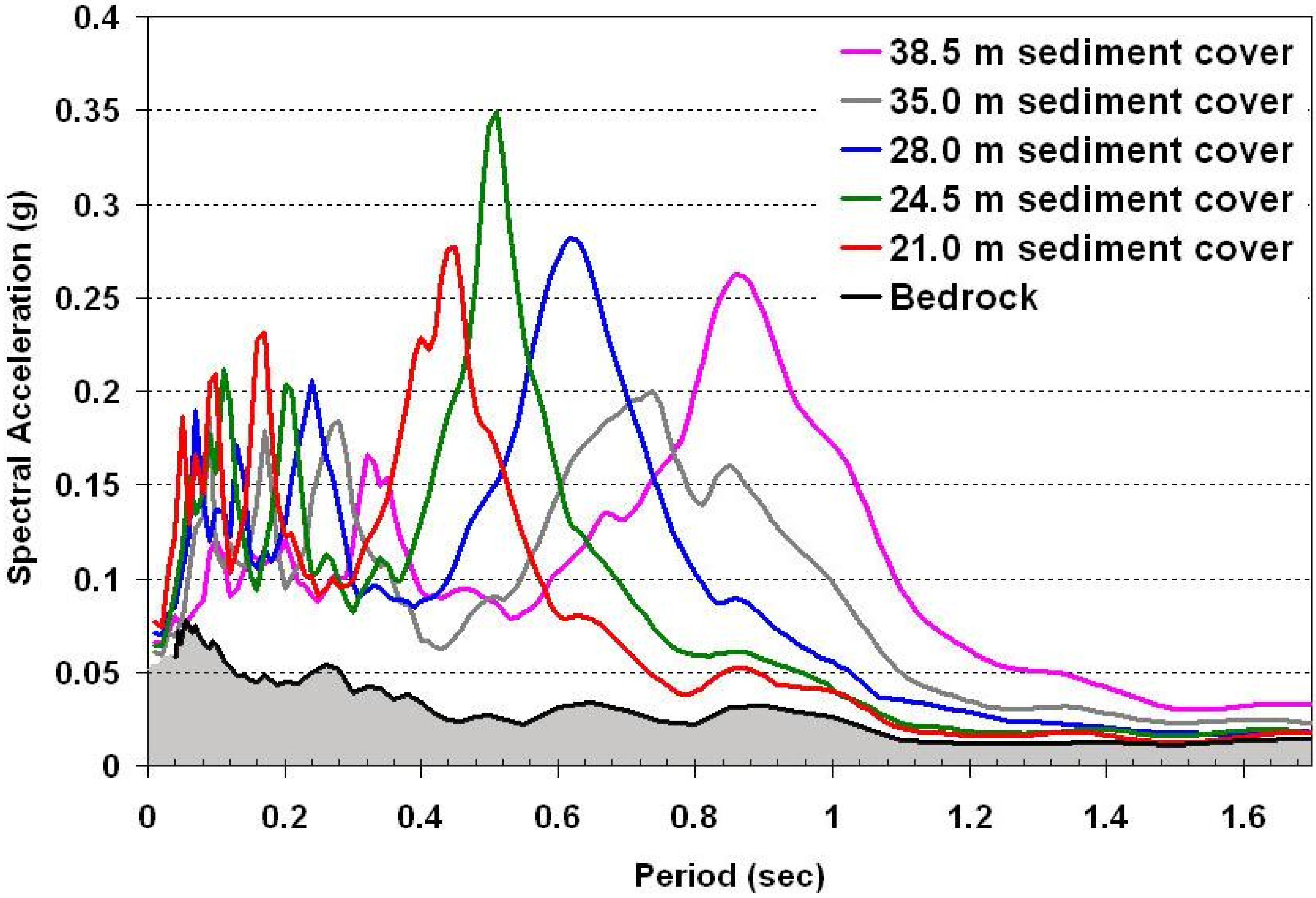






Soil Thickness: 39 m

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**

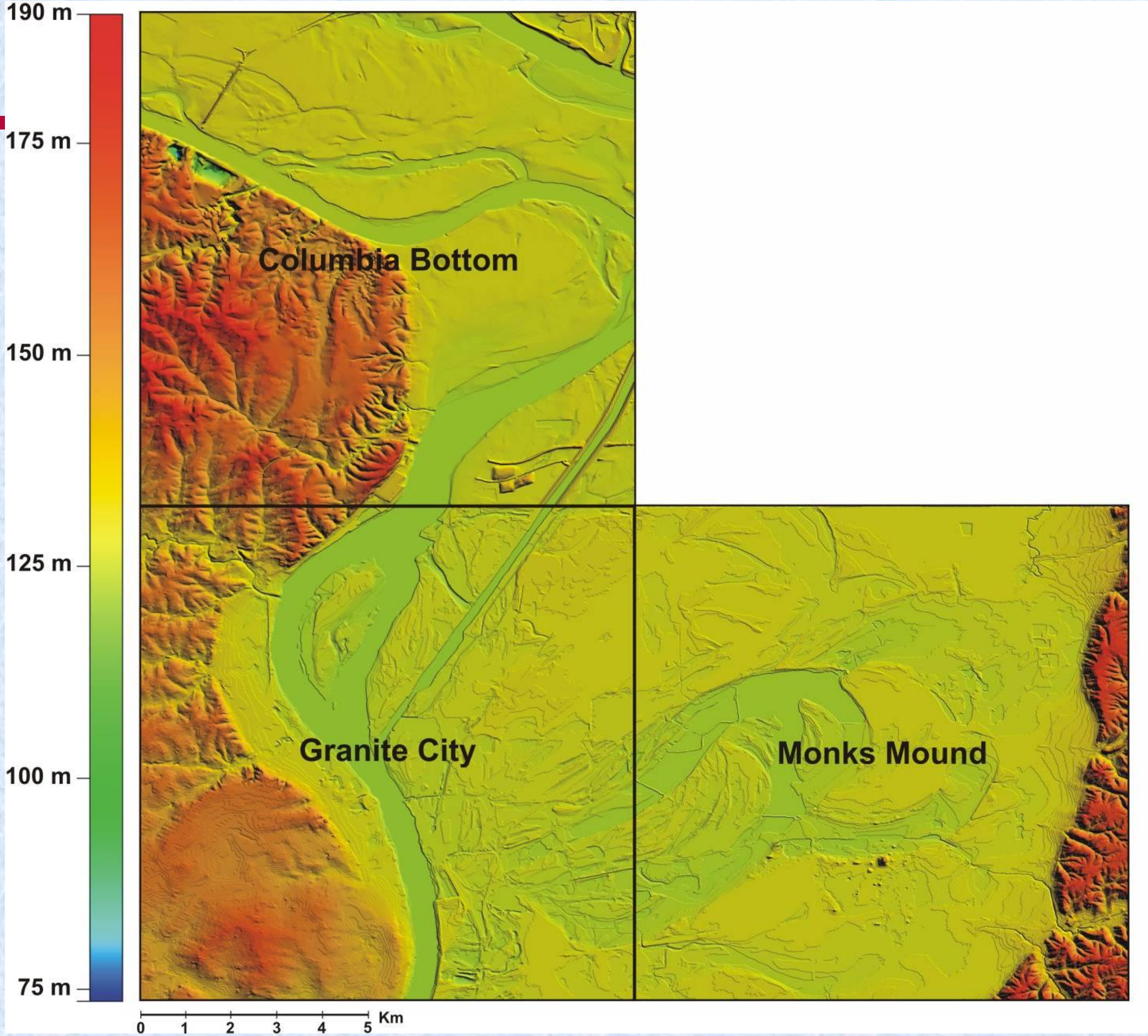
3) **Characterize the thickness and shear wave velocity of the bedrock underlying the surficial materials**

4) **Characterize the properties of the surficial materials (~soil cap)**

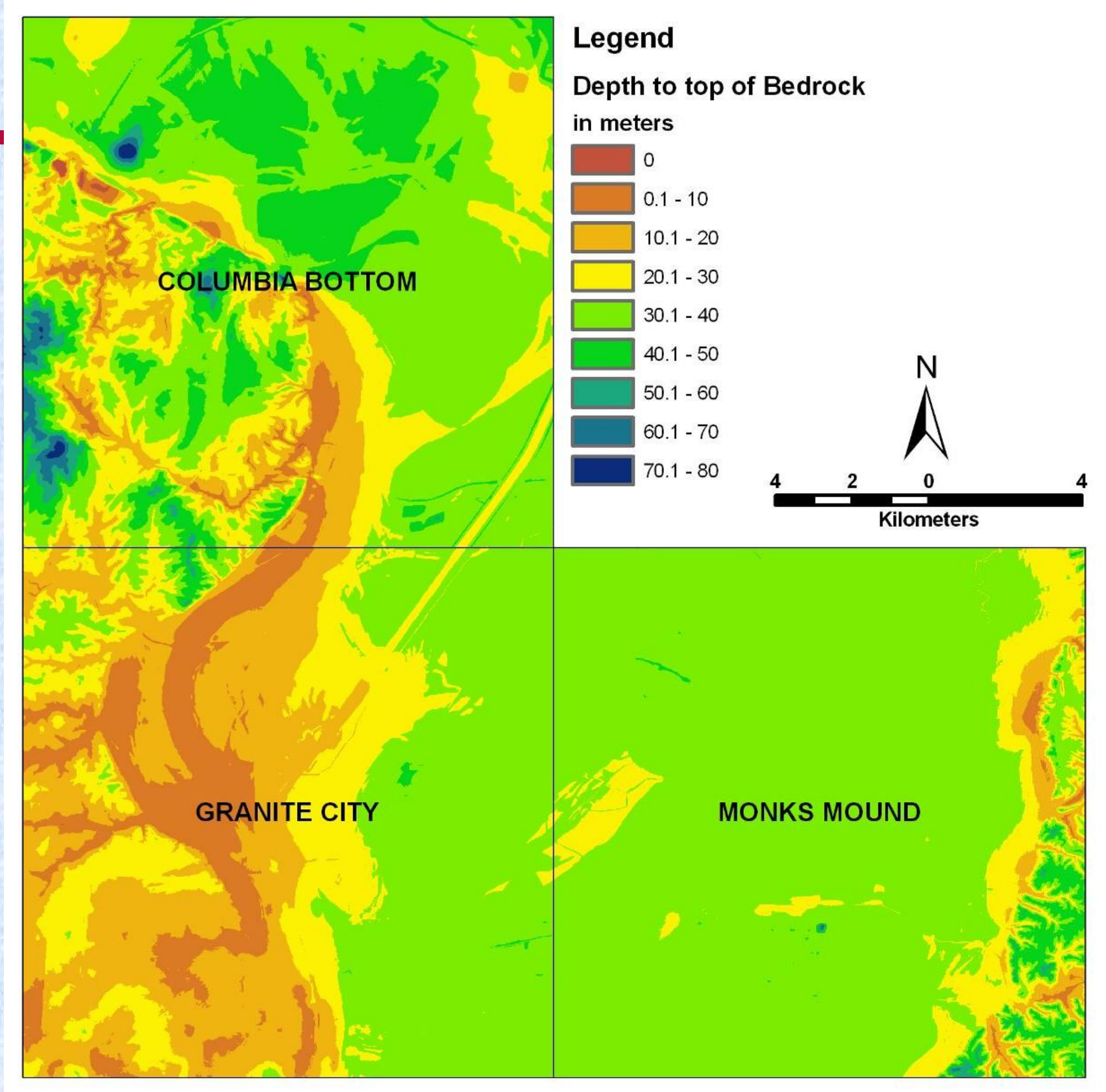
   Physical soil properties

   Dynamic soil properties (shear modulus and damping, shear wave velocity)

Digital Elevation Model used in pilot study



Depth to Bedrock (Surficial Geology Thickness Map)

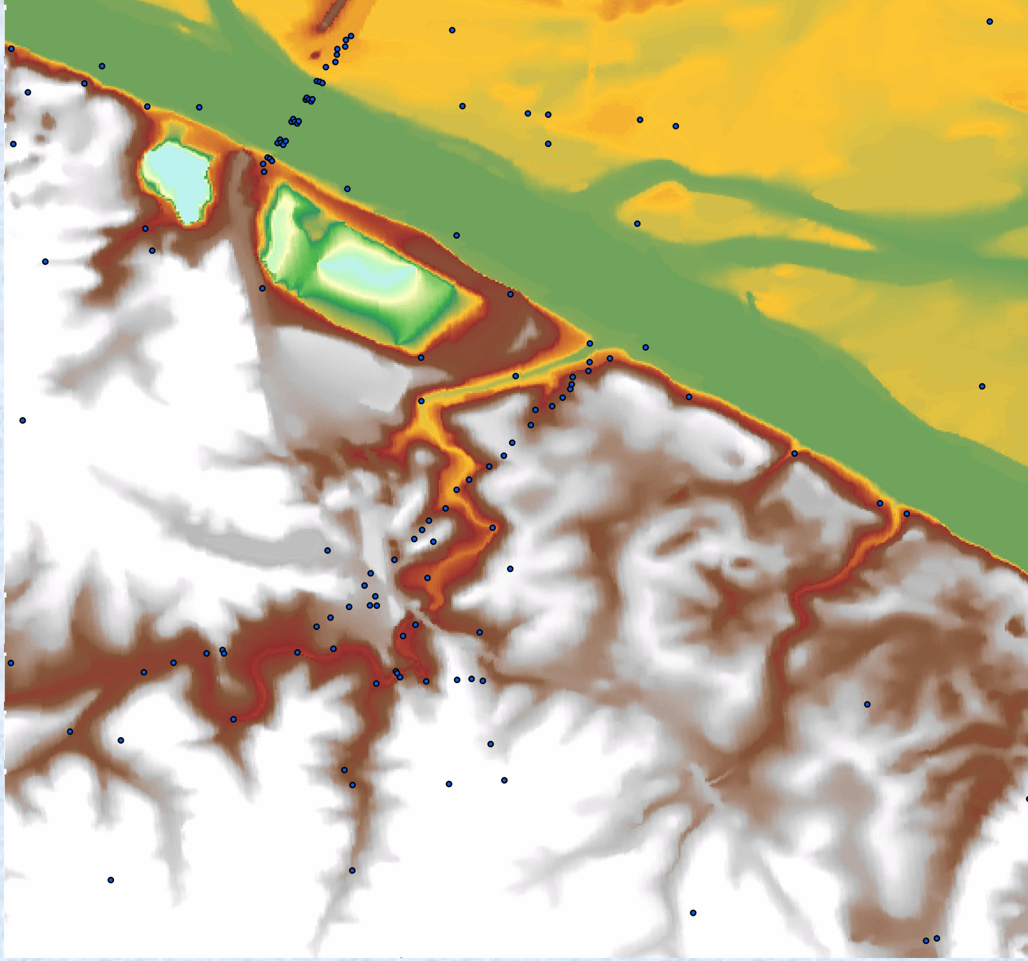


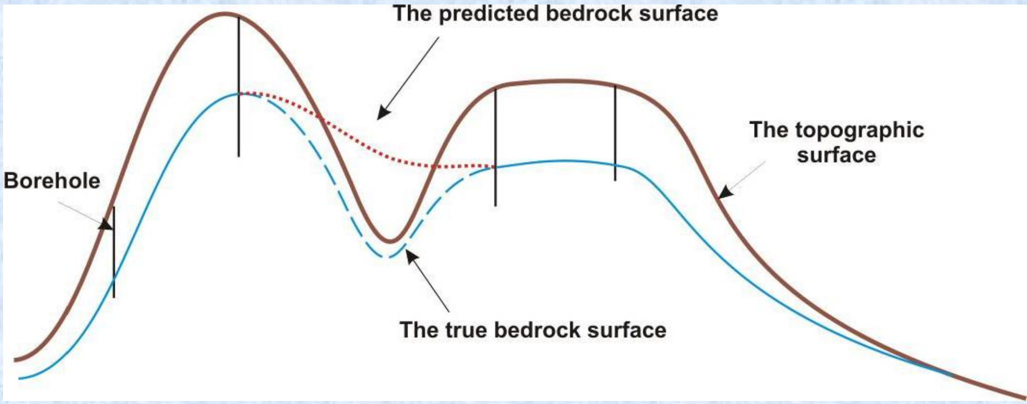
Drawbacks

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.

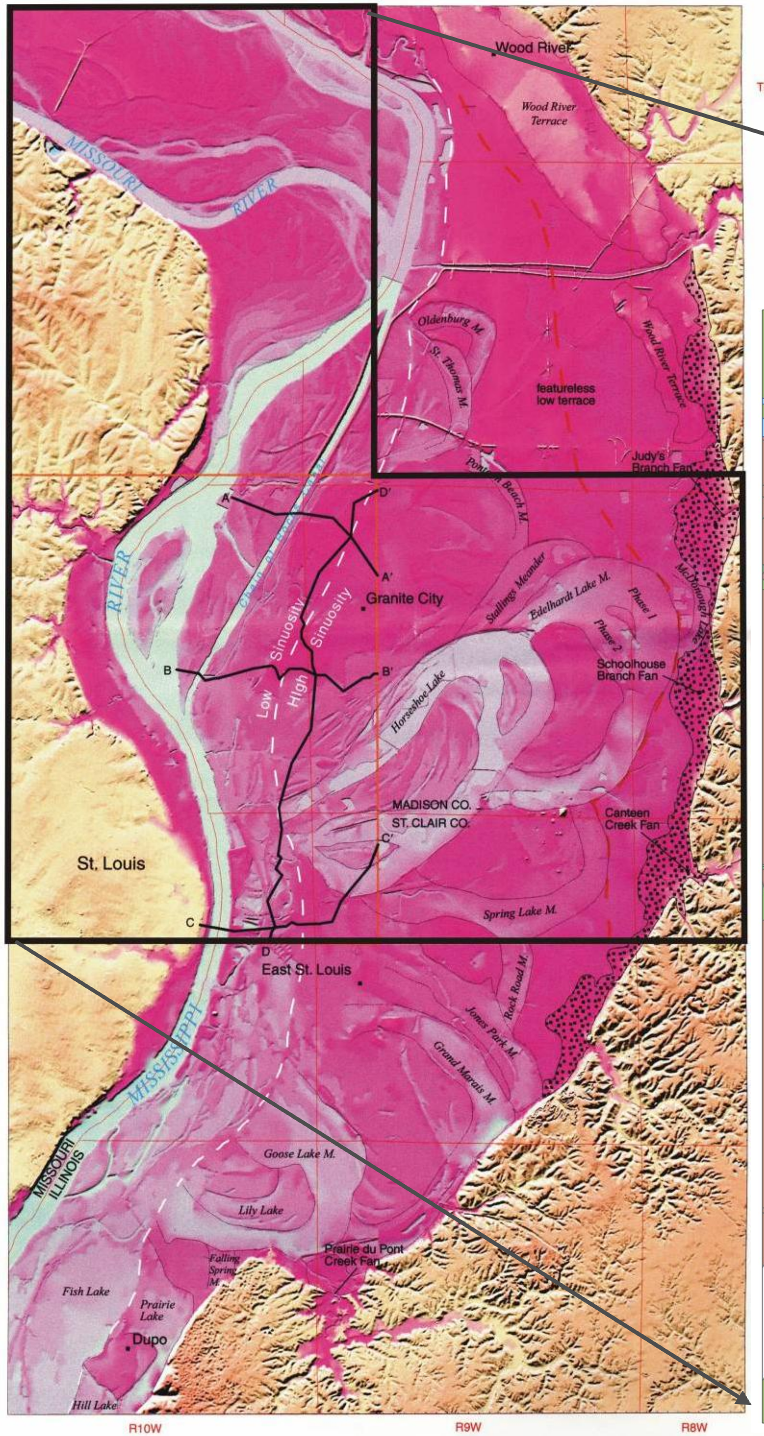
The loess deposits mantling the uplands tend to thicken towards hilltops and thin towards valleys, because of erosion.

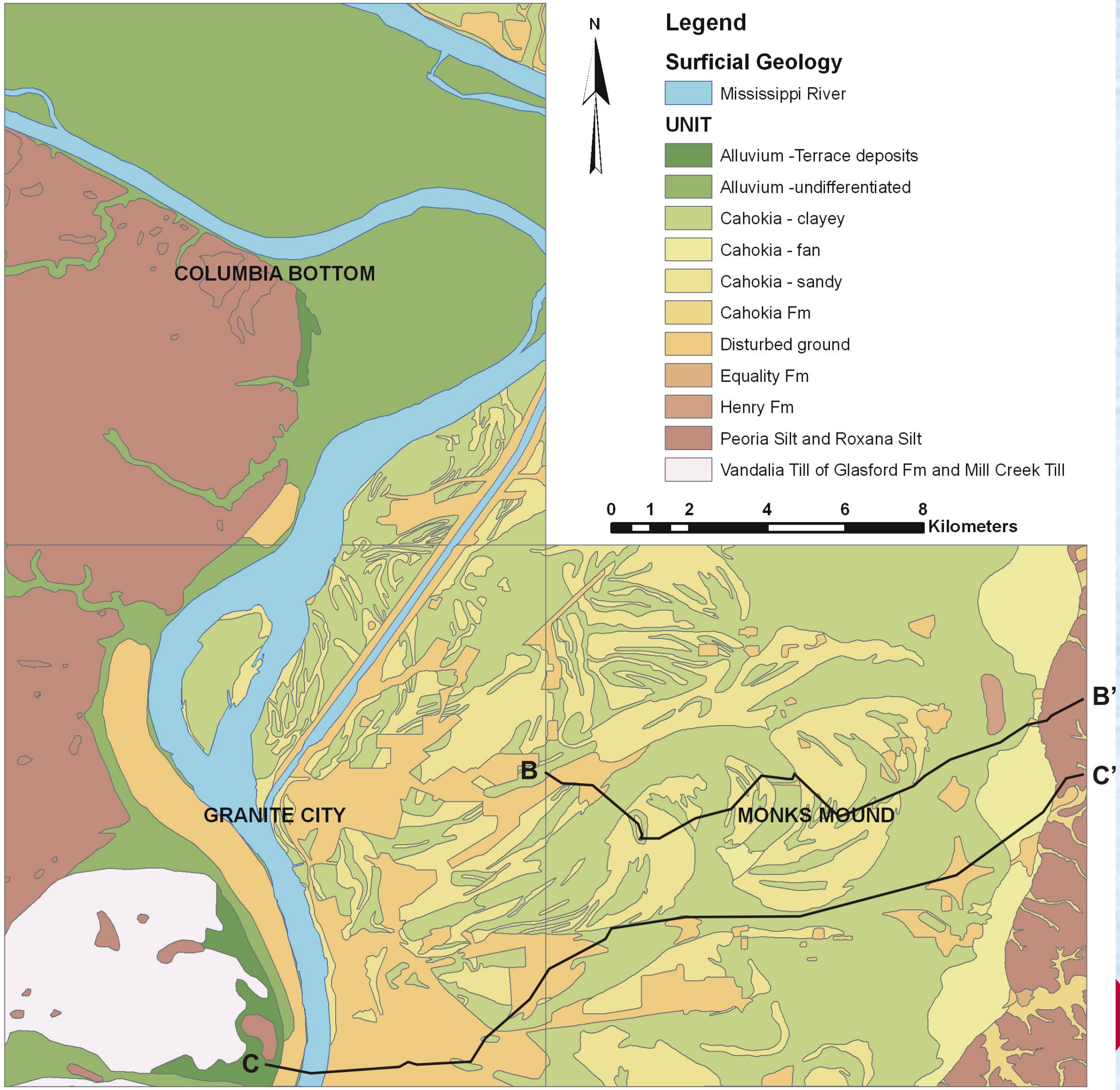
When thickness data is missing in these valleys, kriging techniques can be unreliable, as shown at lower right.





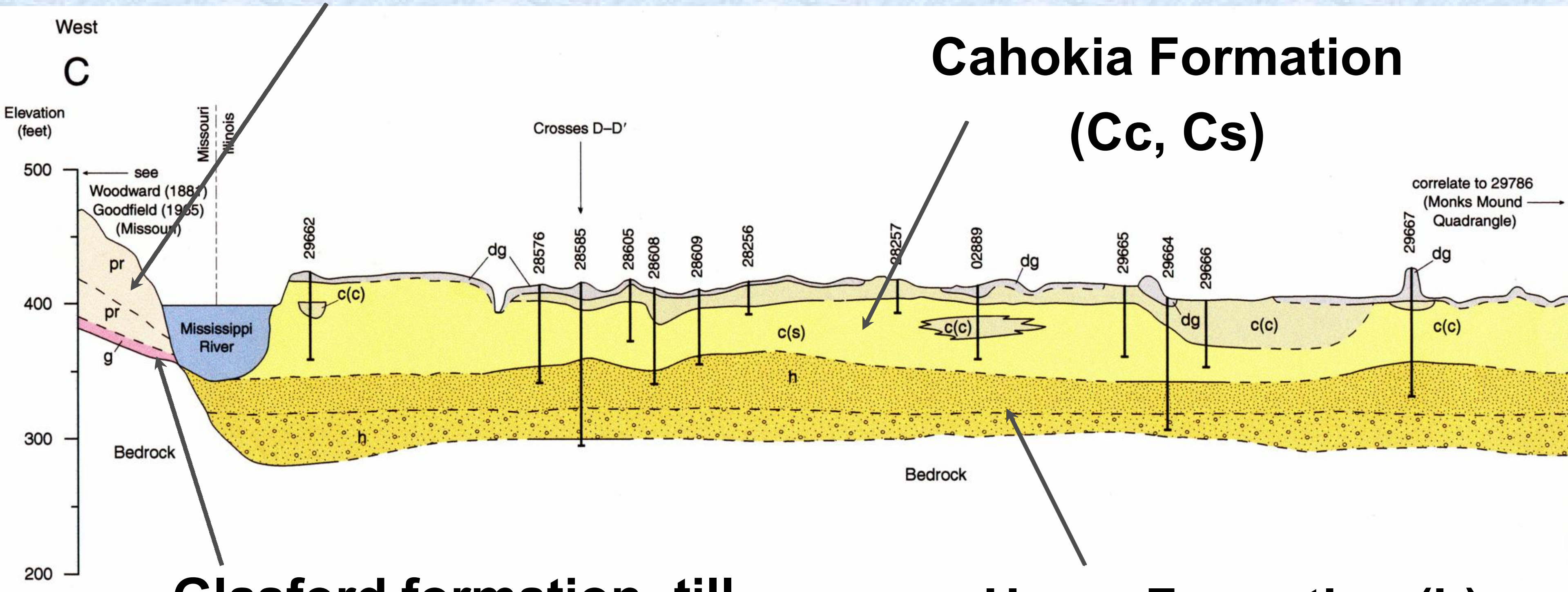
Surficial Geology of St. Louis study area





Typical cross section thru Mississippi River flood plain

Peoria and Roxana Silt and wind-blown loess

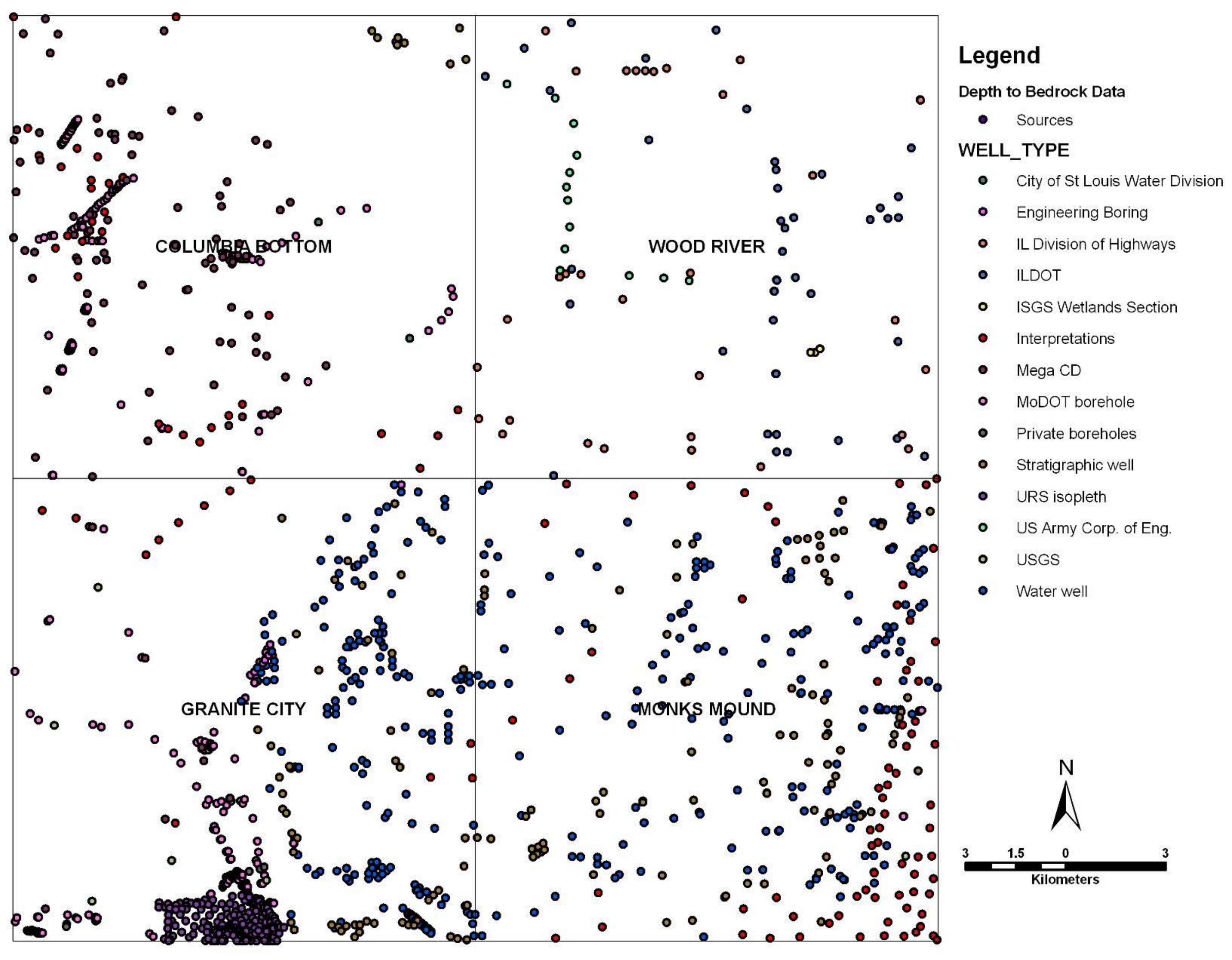


Cahokia Formation (Cc, Cs)

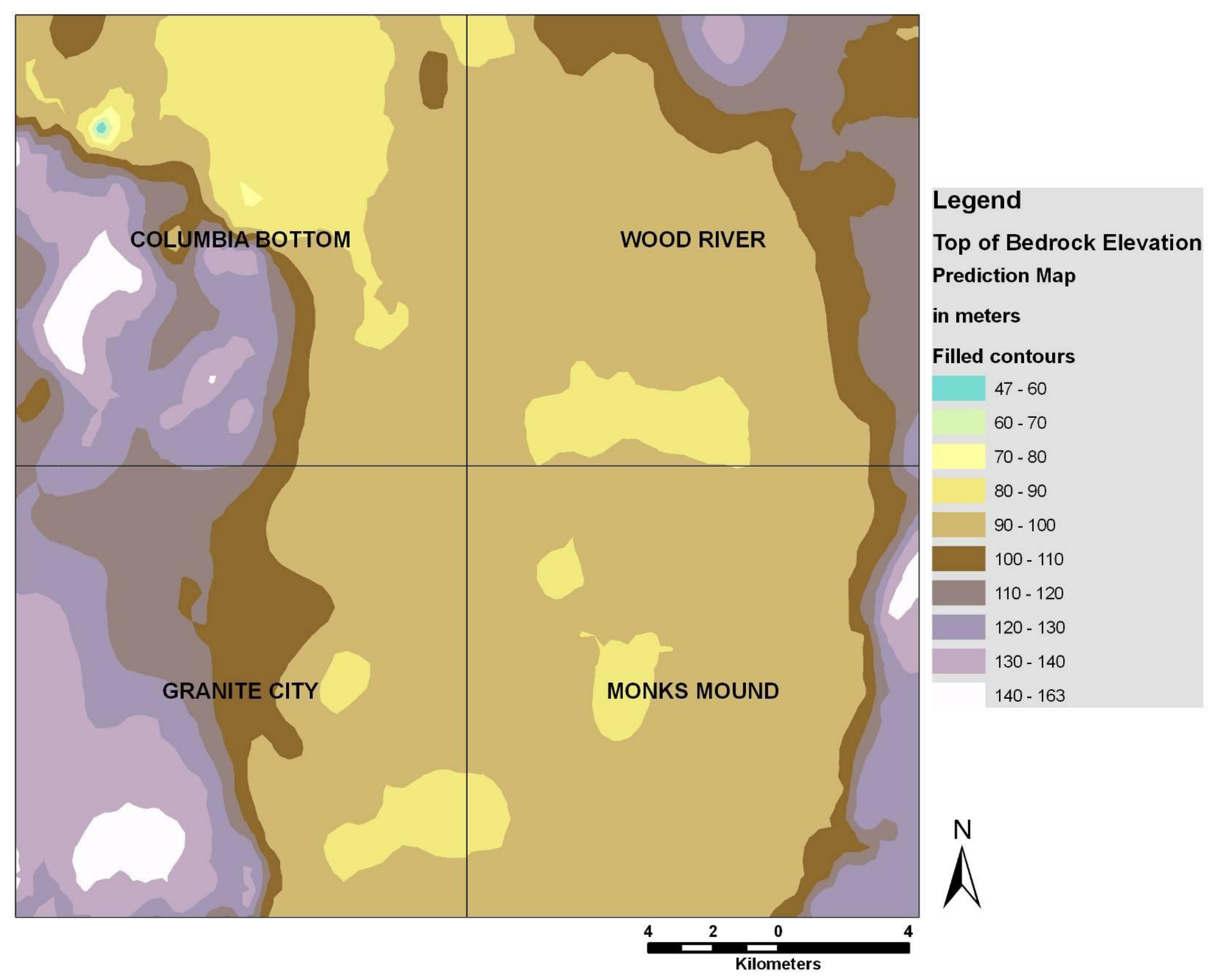
Glasford formation -till

Henry Formation (h)

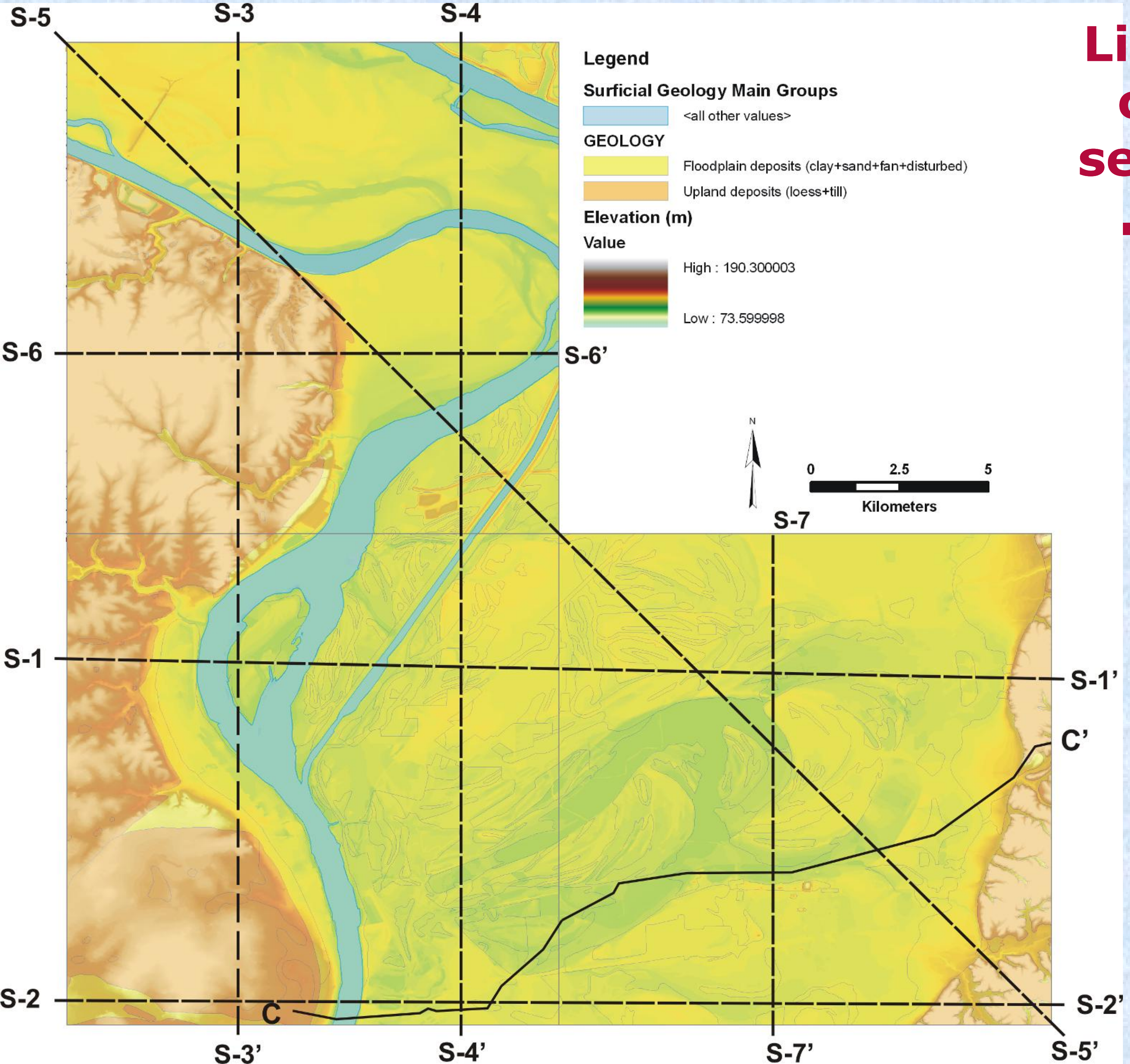
Boreholes Used in the pilot study



Estimation of Top-of-Bedrock Elevations



Lines of cross sections



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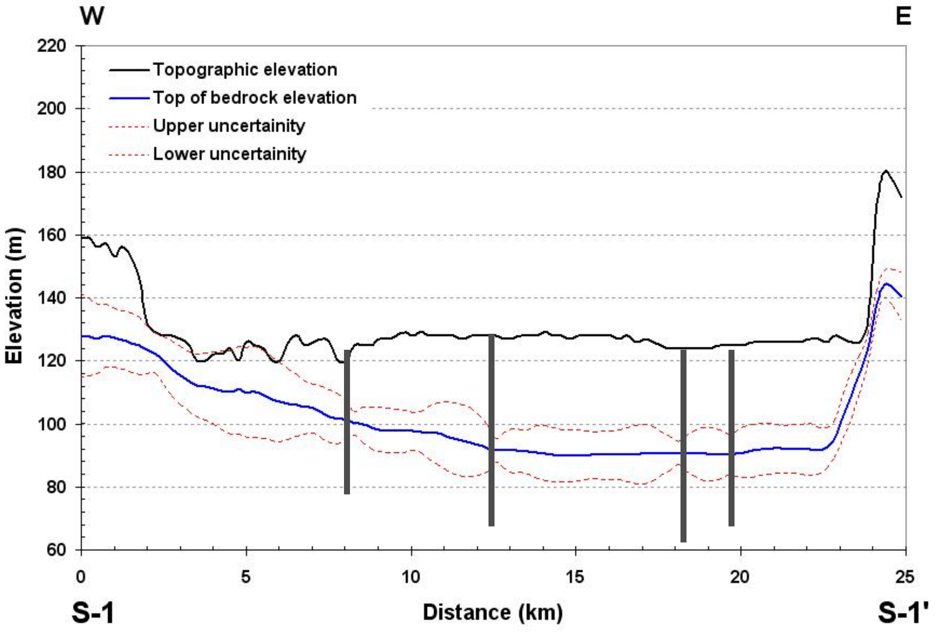
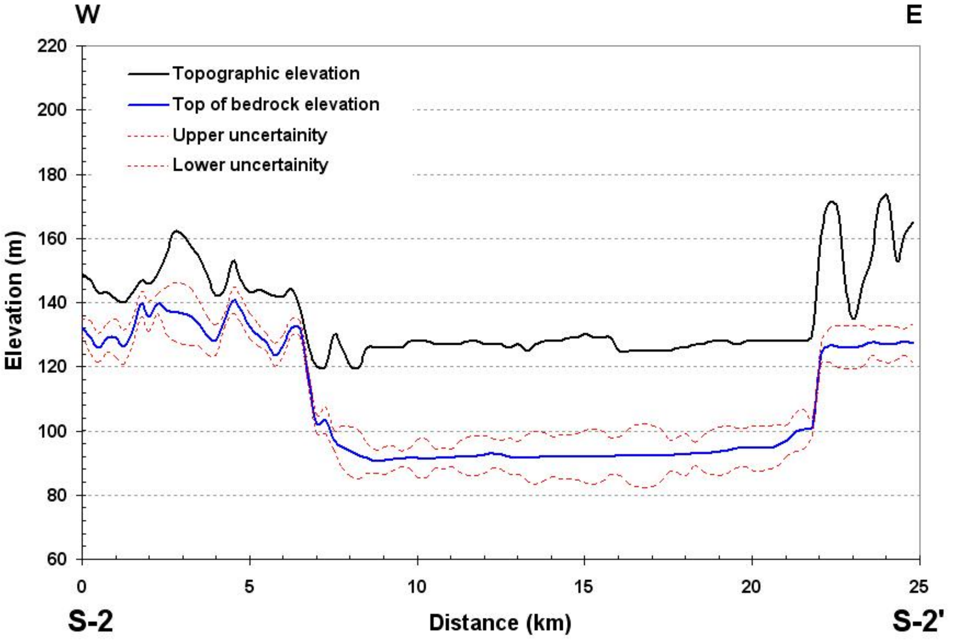
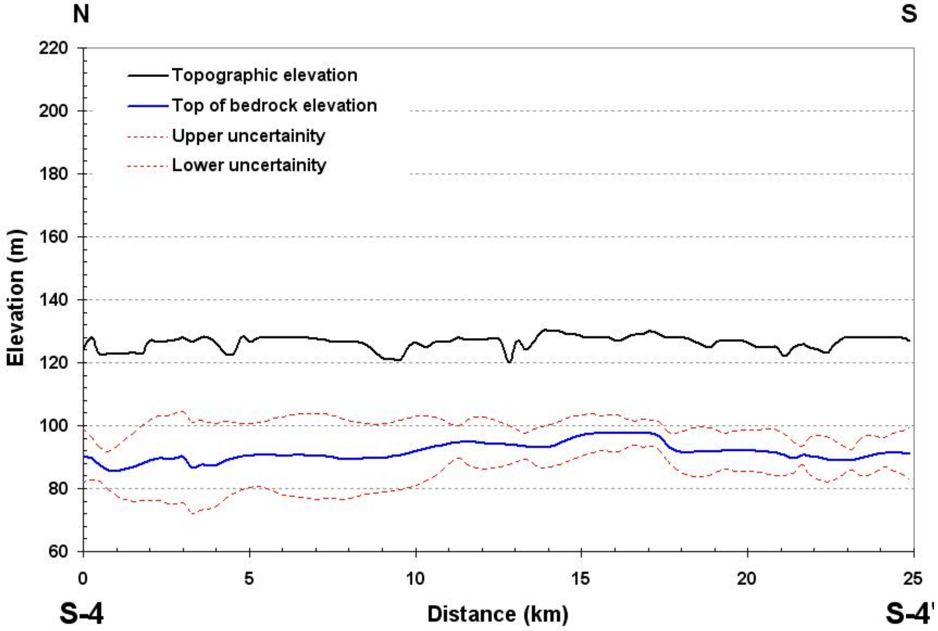
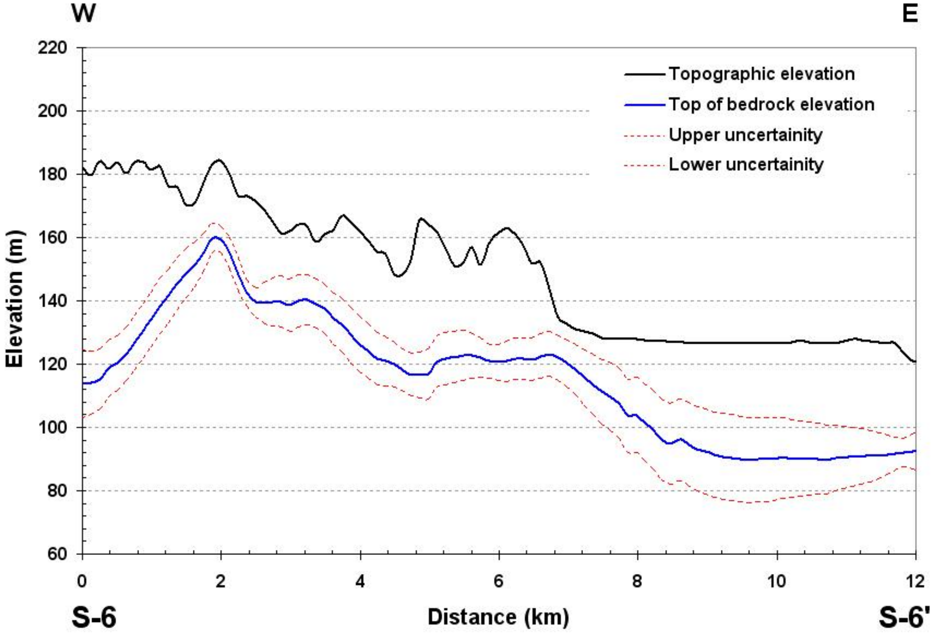




Cross sections with estimates of uncertainty



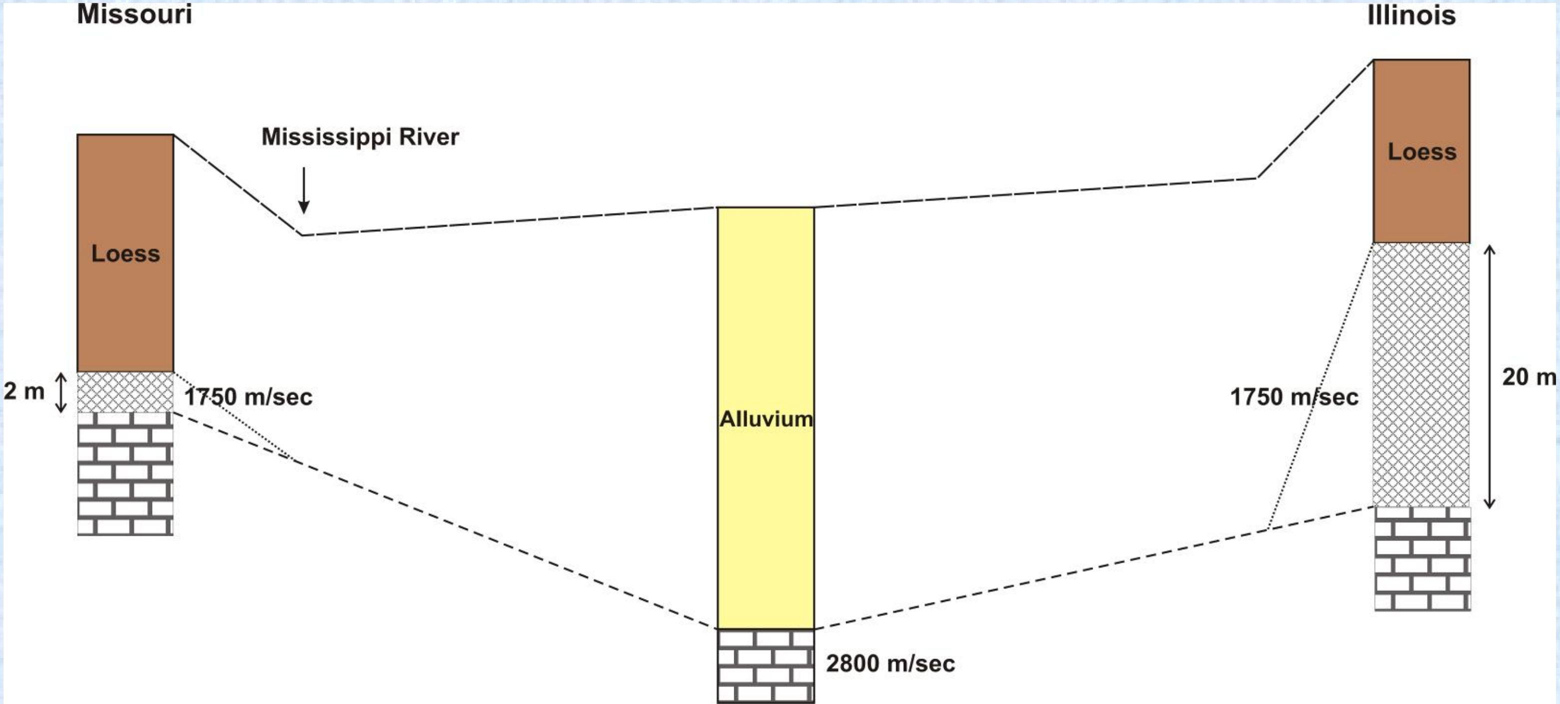


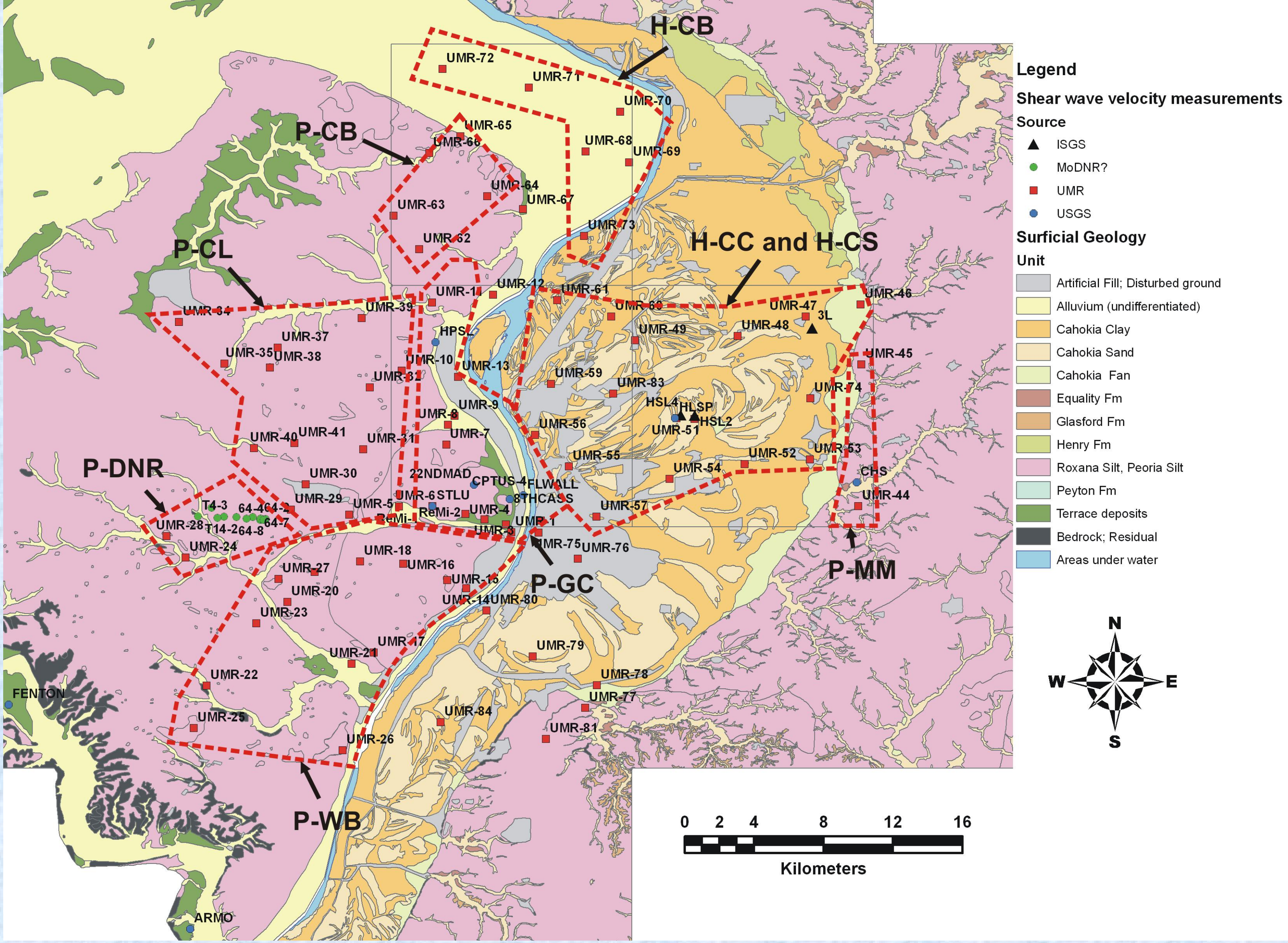
Bedrock properties

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.

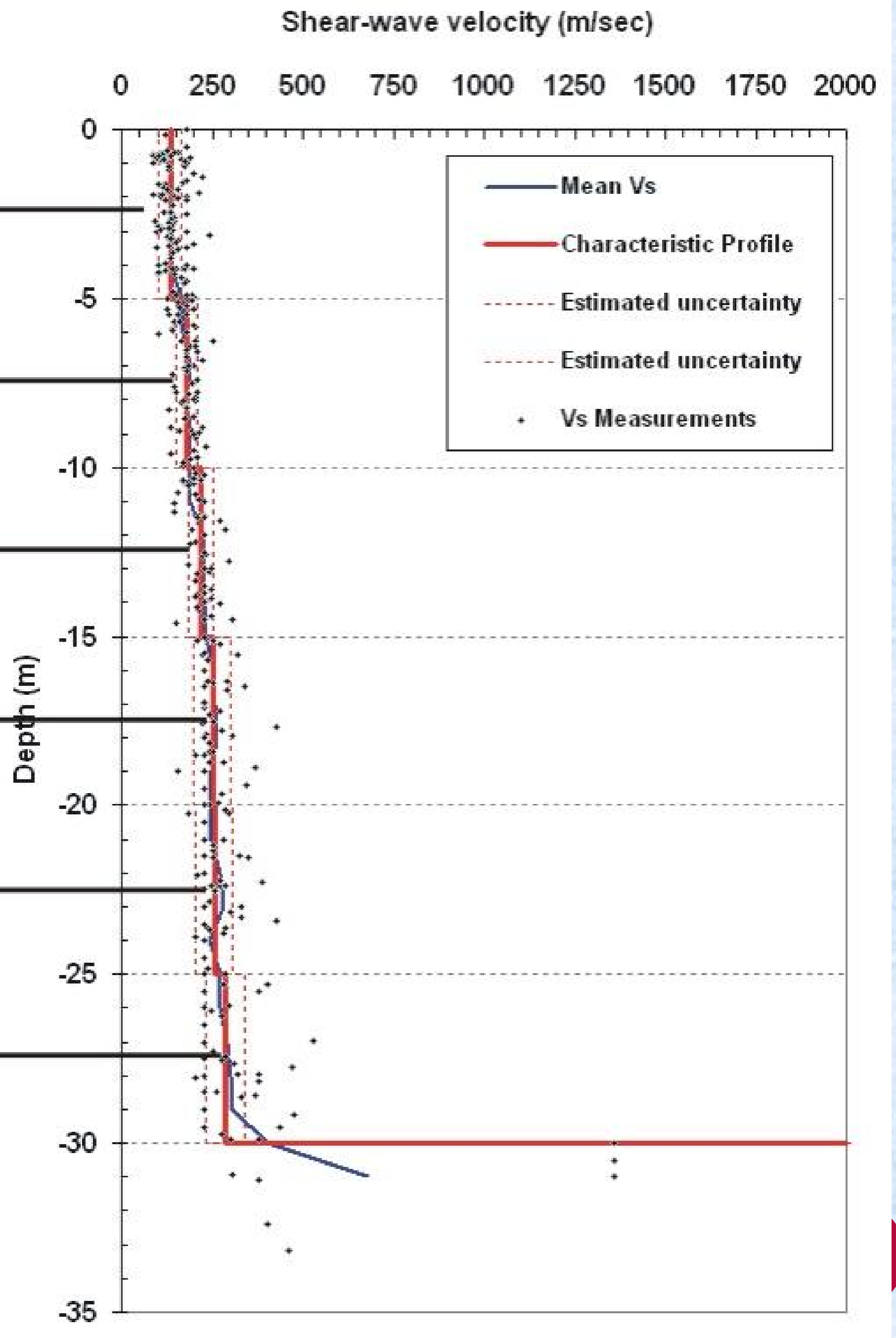




Characteristic Vs profiles were developed for nine geologic/geomorphic terrains, such as alluvial or loess/colluvial covered uplands, etc.

Characteristic Vs Profiles

Floodplain (Alluvial) deposits



Vs = 134 m/s
σ = 33 m/s

Vs = 180 m/s
σ = 30 m/s

Vs = 218 m/s
σ = 34 m/s

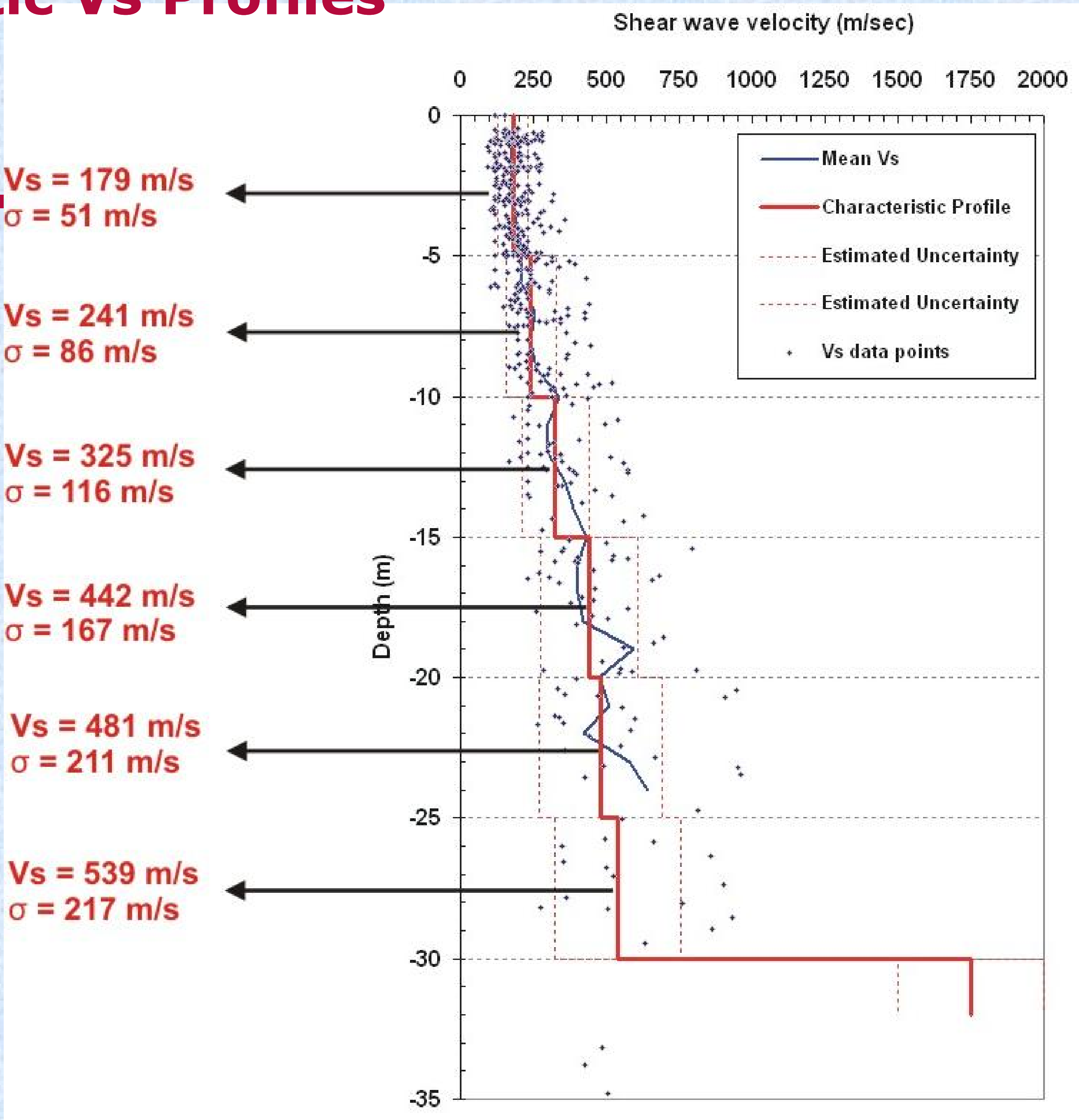
Vs = 250 m/s
σ = 50 m/s

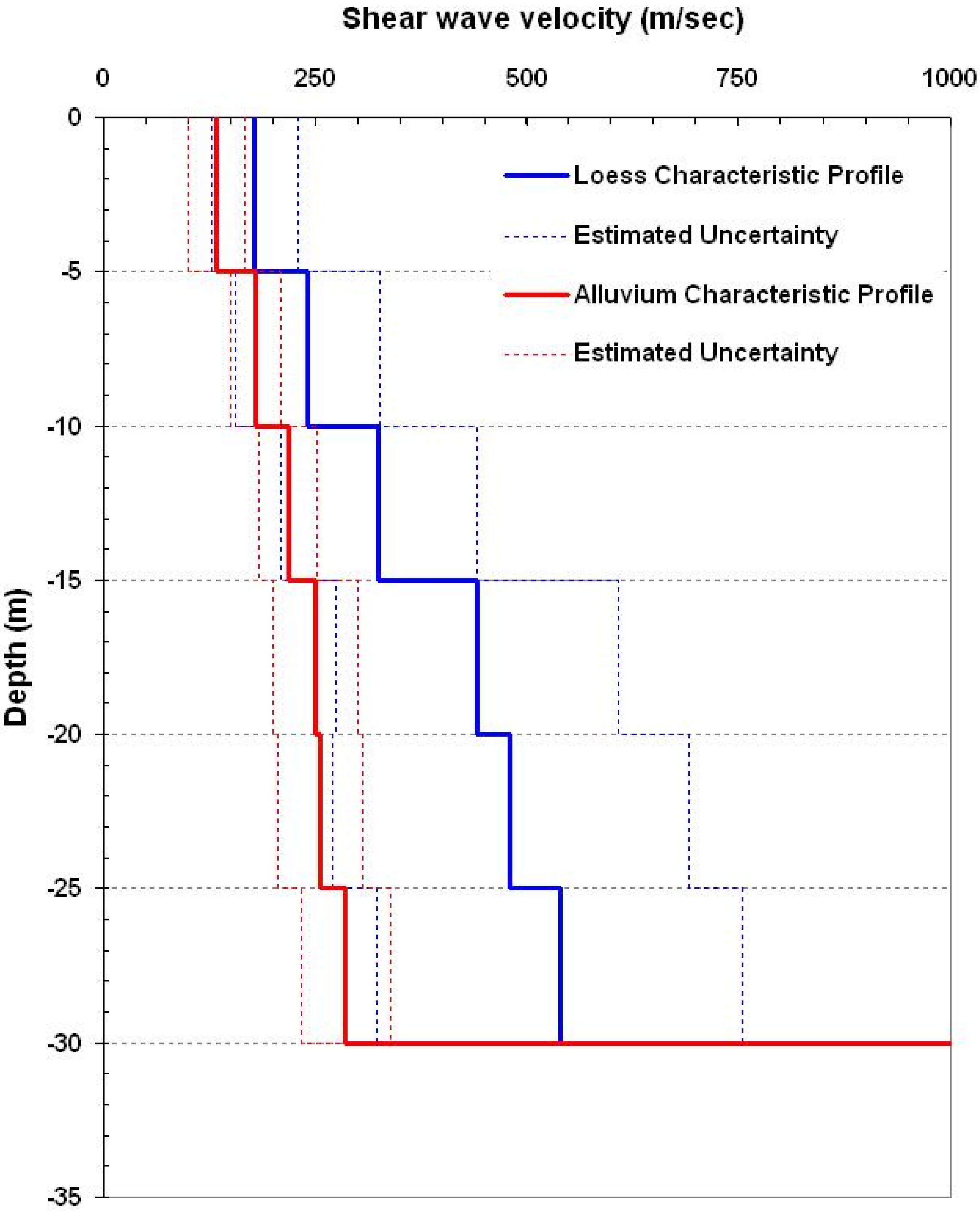
Vs = 256 m/s
σ = 50 m/s

Vs = 286 m/s
σ = 53 m/s

Characteristic Vs Profiles

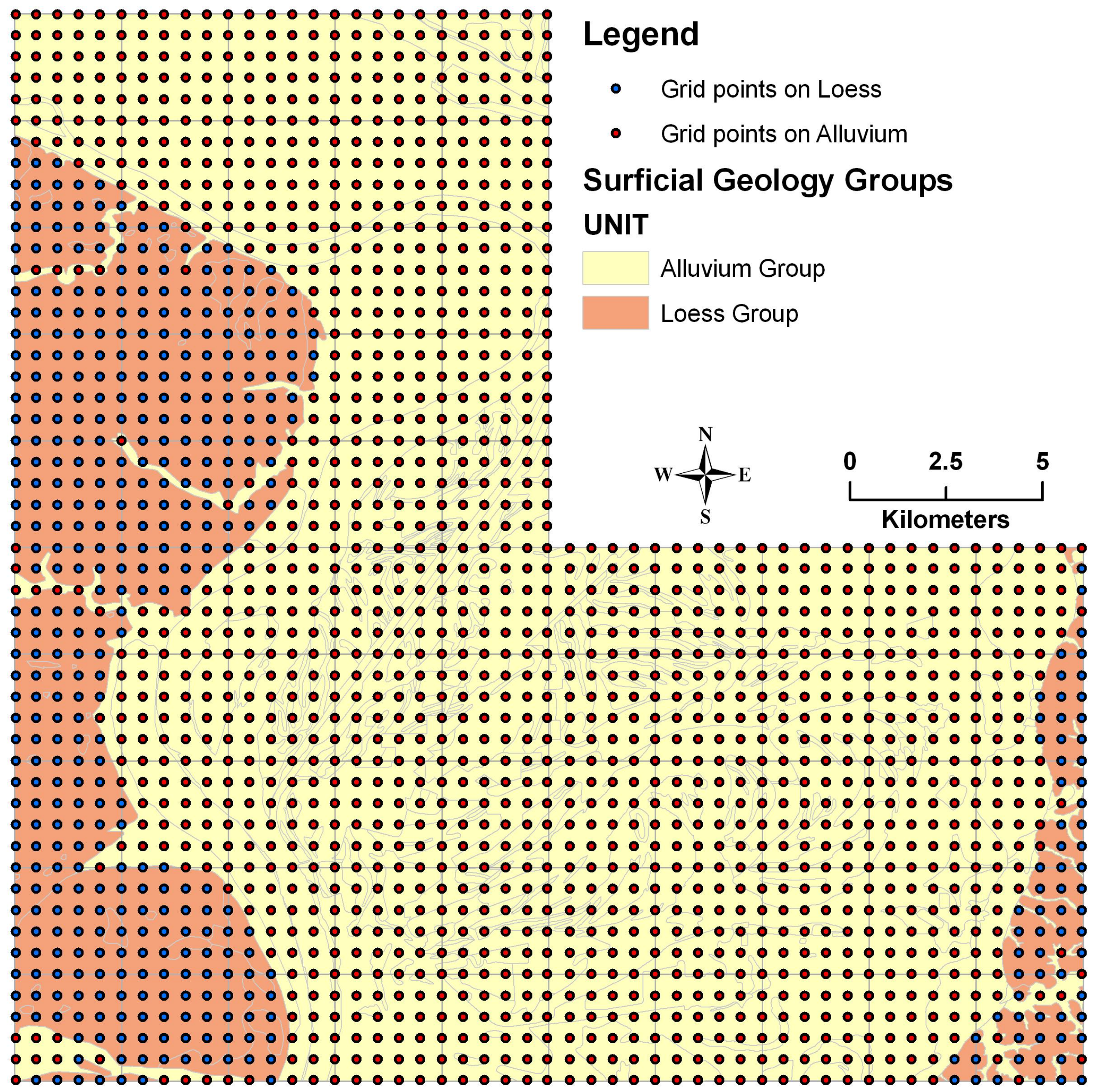
Loess-covered Upland deposits





Comparisons between Vs profiles for Alluvium in the major river valleys and the Loess covered uplands

Amplification Calculation Procedure



Total of 1,974 grid points, 500 m apart

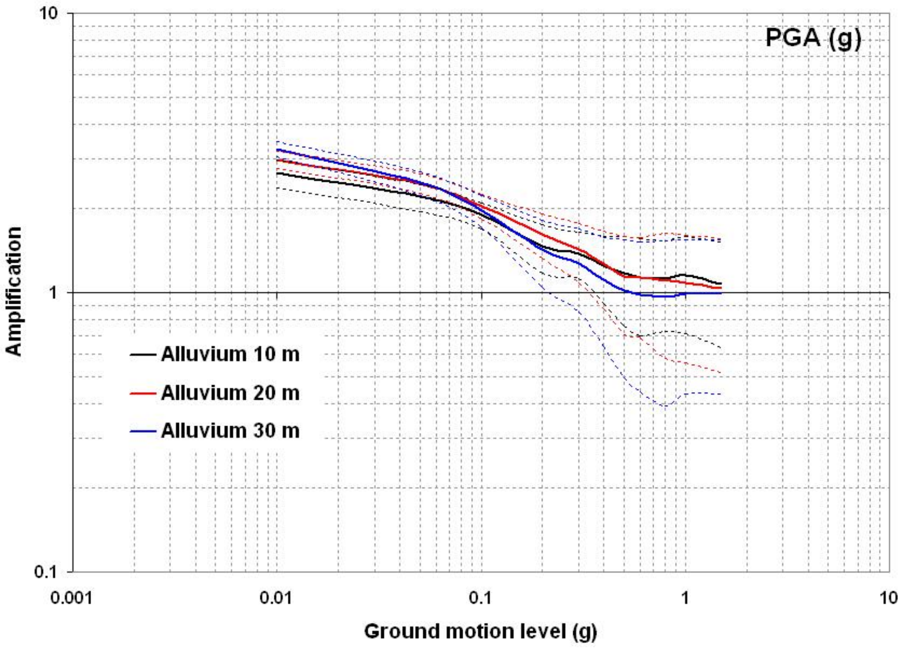
For every grid point, calculations were performed 100 times for the 10 ground-motion levels and three ground motion parameters (PGA, 0.2sec Sa, and 1 sec Sa), bringing the total to 3000 calculations per grid point.

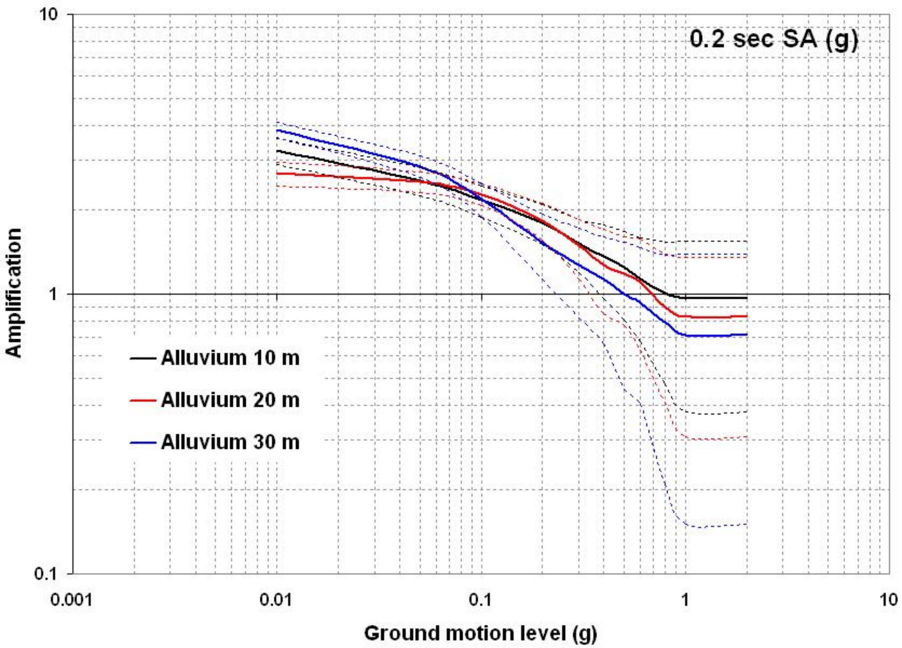
When multiplied to the total number of grid points, more than 5,400,000 calculations were made.

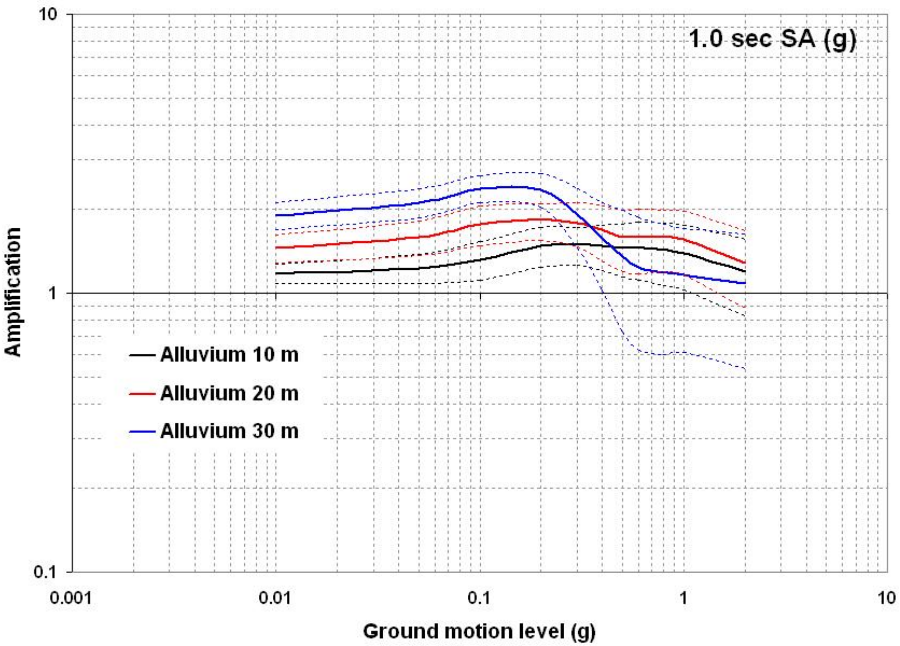
Step 6

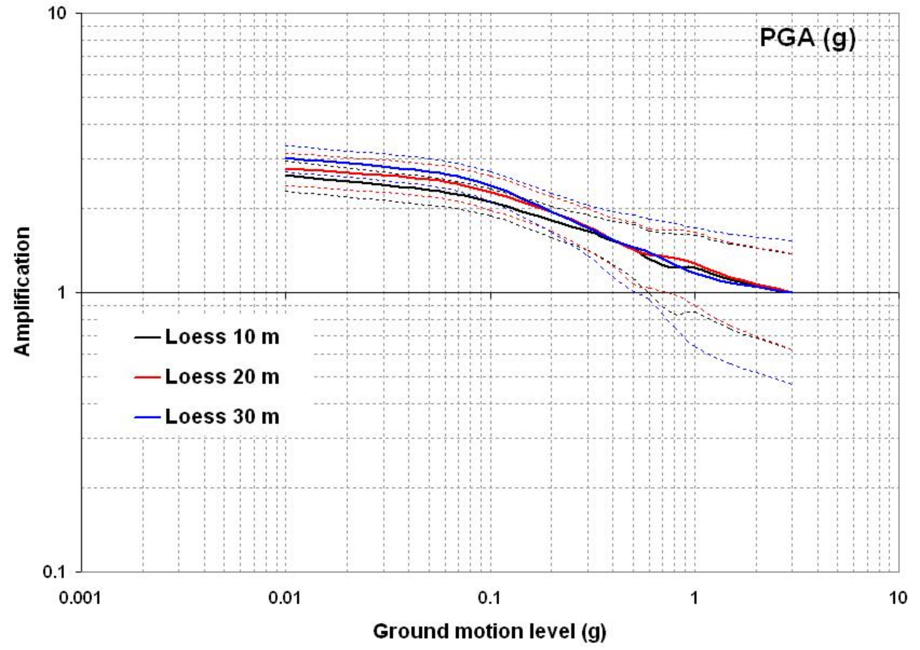
Distribution of Site Amplification

Distribution of Site Amplification in Alluvium

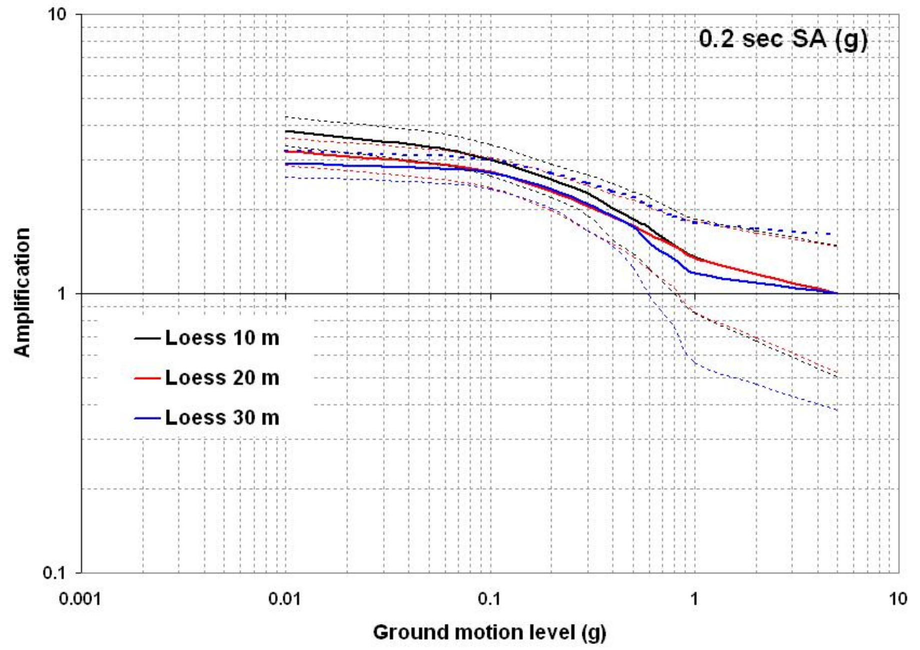


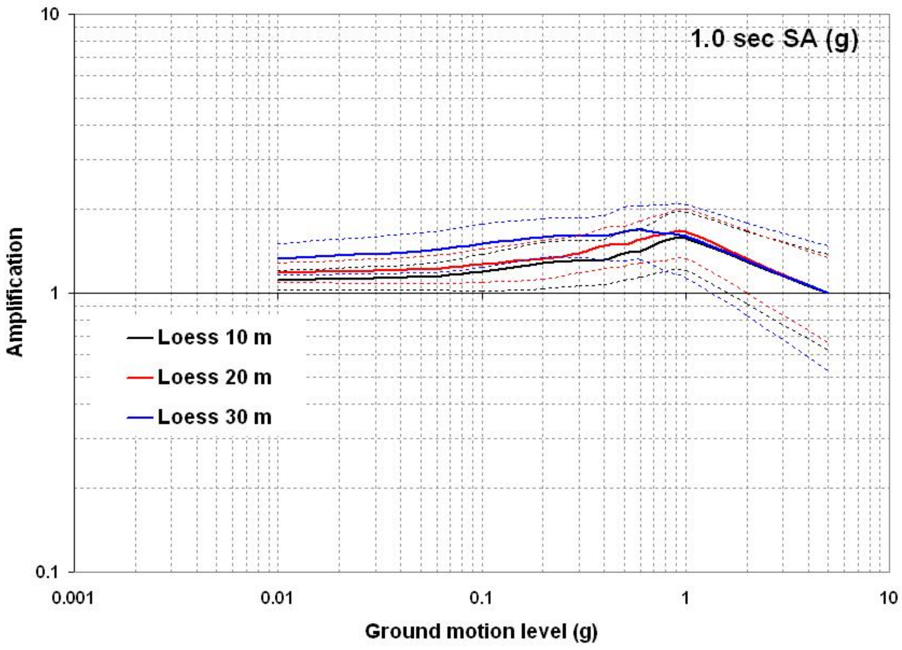




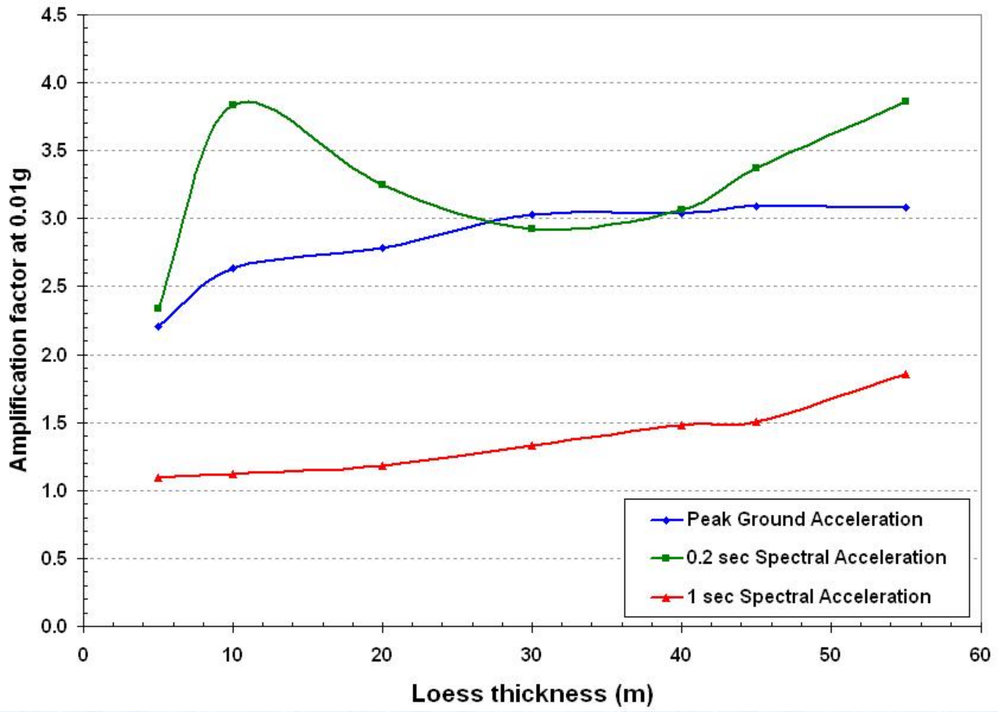


Distribution of Site Amplification in Loess



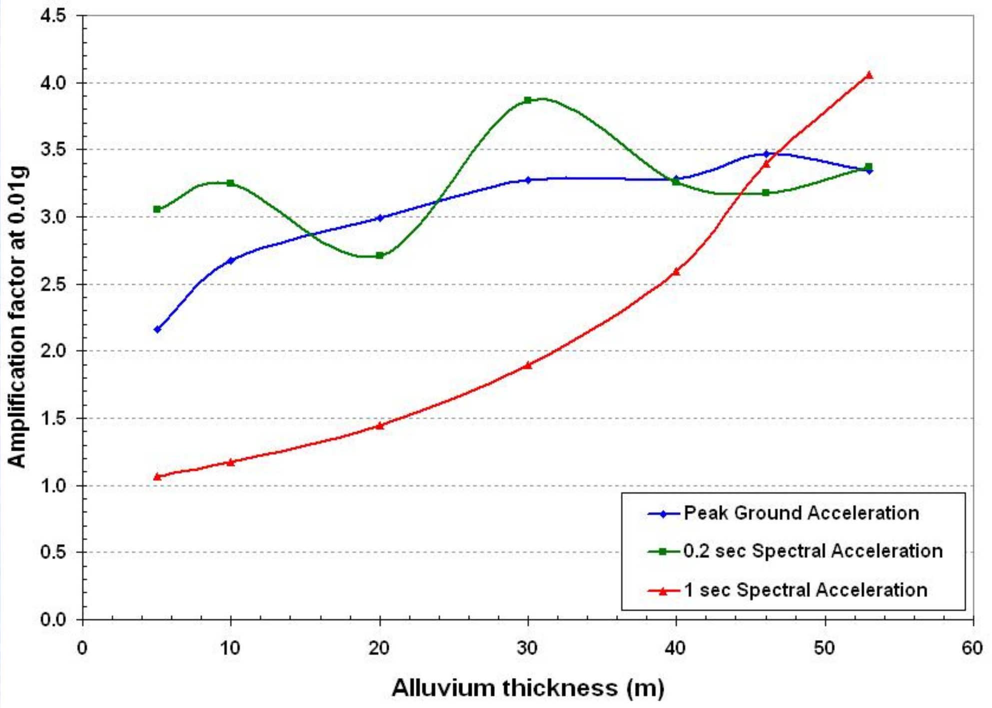


Soil Cap Thickness
vs.
Ground motion



Upland Profiles

Floodplain Profiles



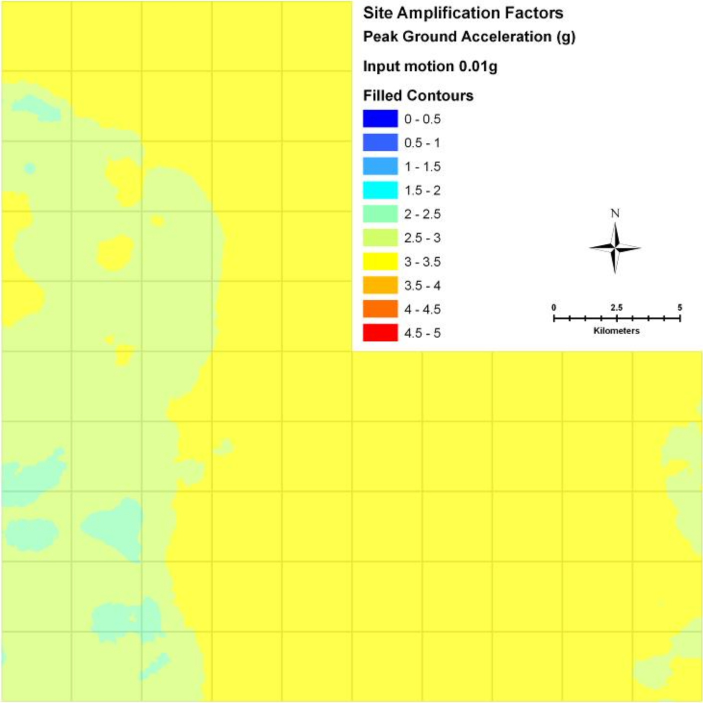
Step 7

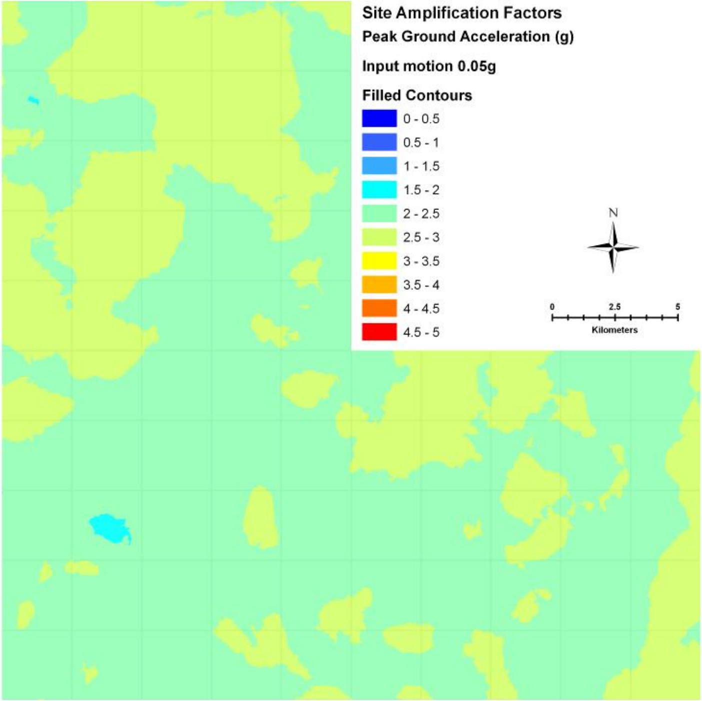
Site Amplification Maps

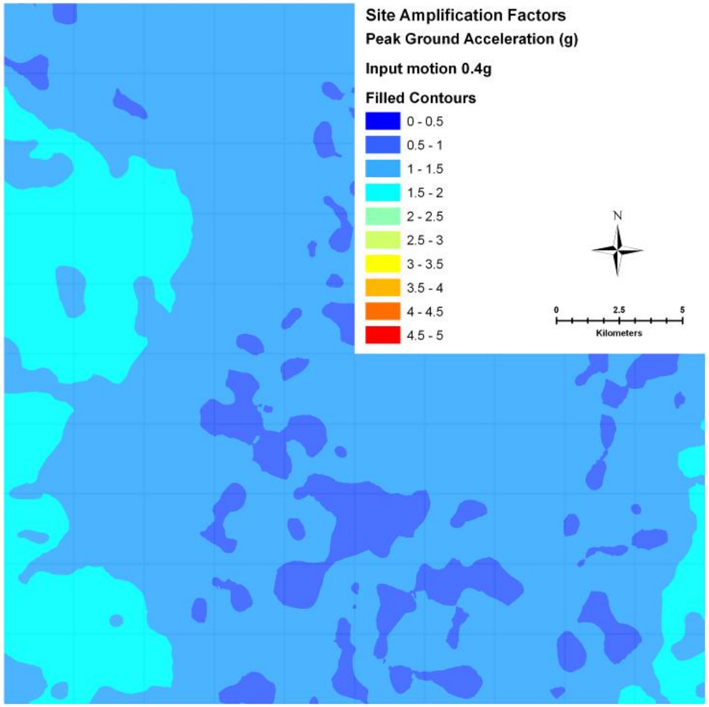
Site amplification maps were generated for discrete increments of ground motion(0.01 to 1.0 g) and for the following ground motion parameters:

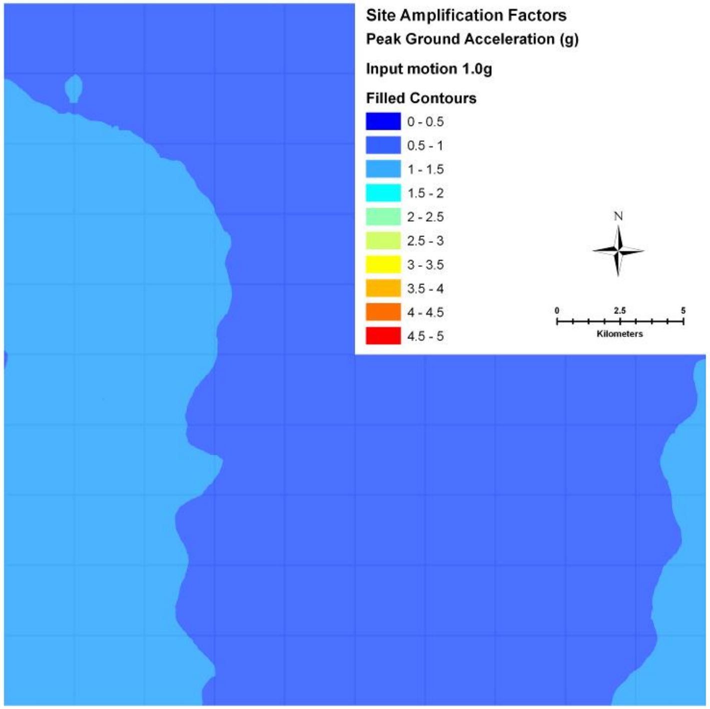
- **Peak Ground Acceleration (PGA)**
- **0.2 second Spectral Acceleration**
- **1.0 second Spectral Acceleration**

PGA (g)

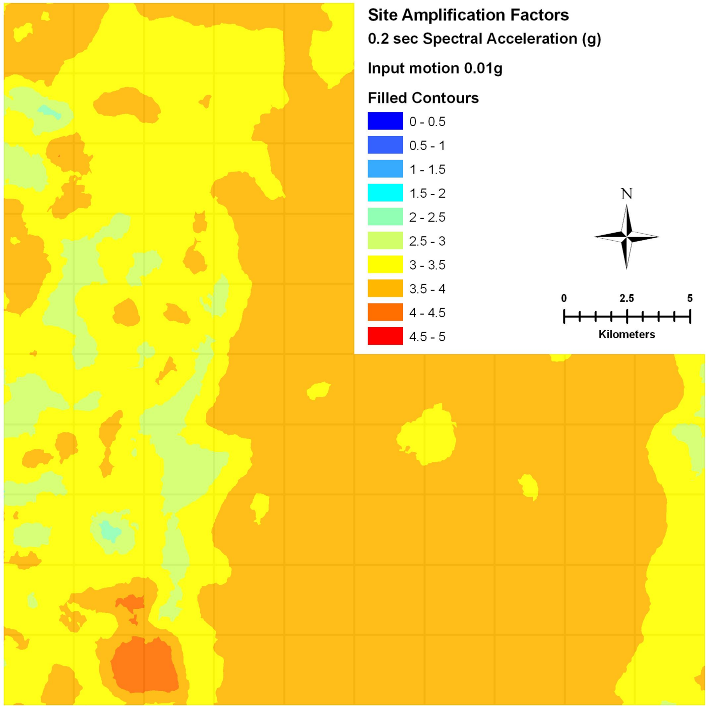

Site Amplification Factors
Peak Ground Acceleration (g)
Input motion 0.01g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers

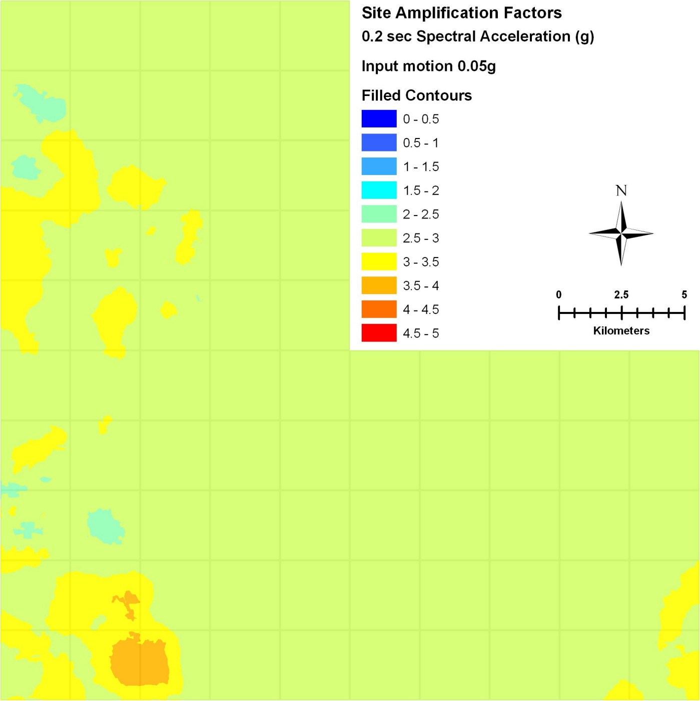

Site Amplification Factors
Peak Ground Acceleration (g)
Input motion 0.05g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers

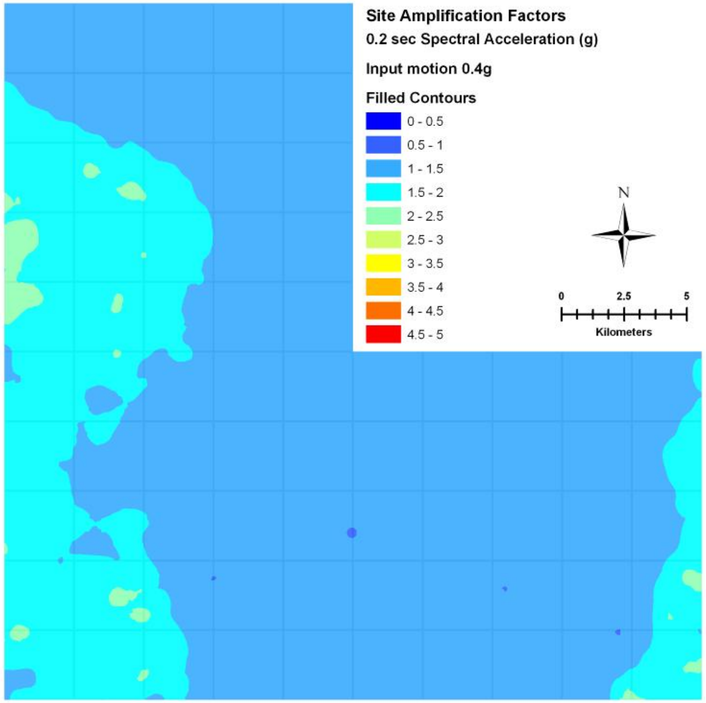

Site Amplification Factors
Peak Ground Acceleration (g)
Input motion 0.4g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers

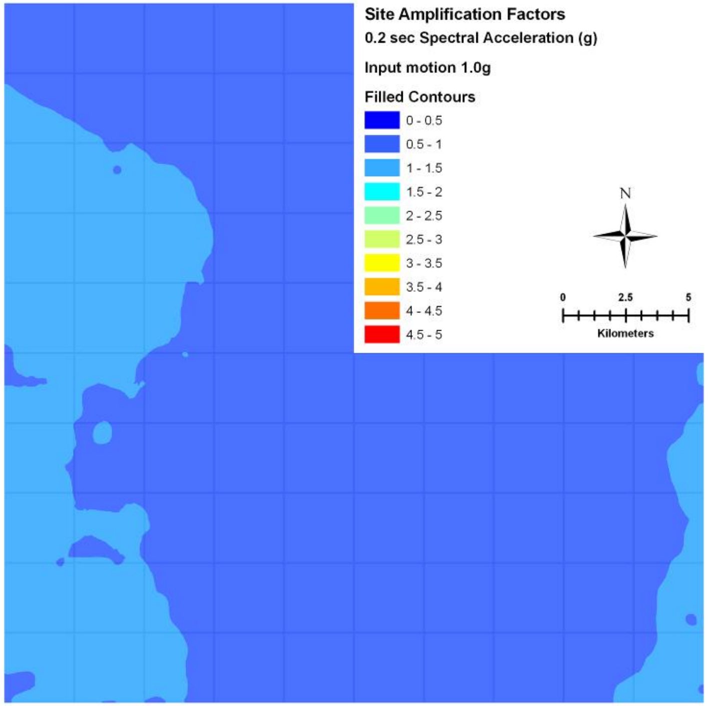

Site Amplification Factors
Peak Ground Acceleration (g)
Input motion 1.0g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers

0.2 sec SA

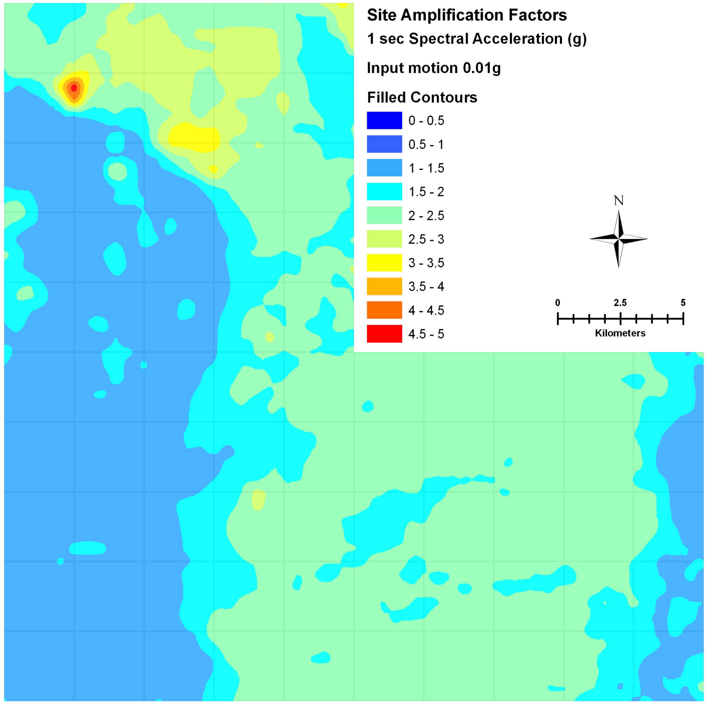

Site Amplification Factors
0.2 sec Spectral Acceleration (g)
Input motion 0.01g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers

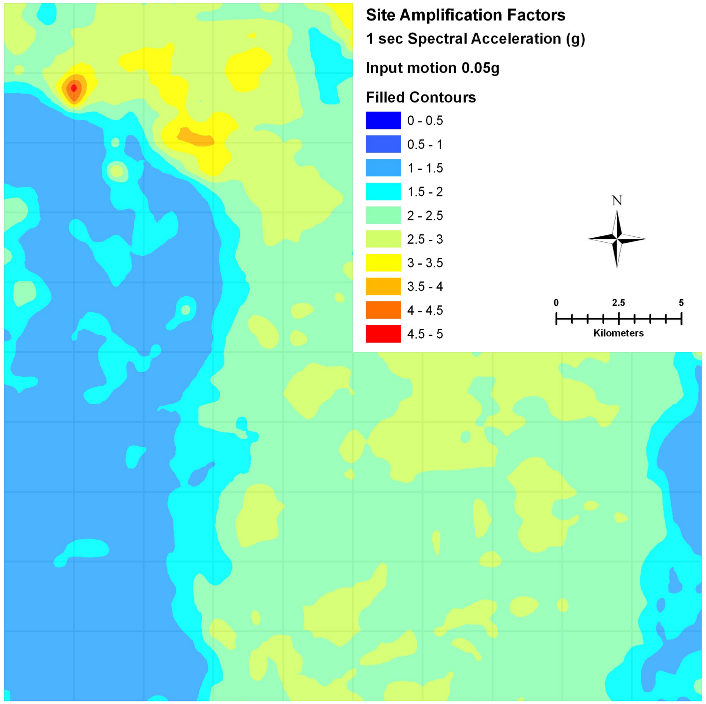

Site Amplification Factors
0.2 sec Spectral Acceleration (g)
Input motion 0.05g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers

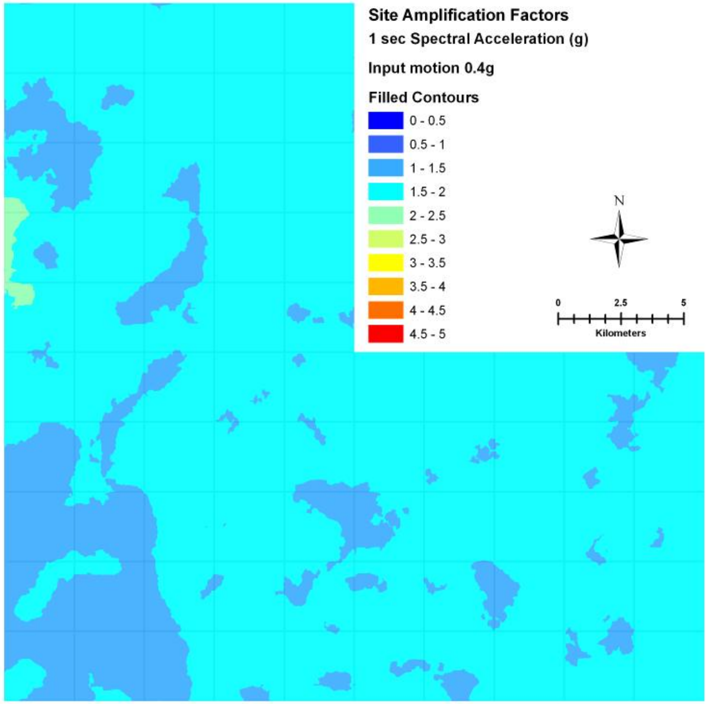

Site Amplification Factors
0.2 sec Spectral Acceleration (g)
Input motion 0.4g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers

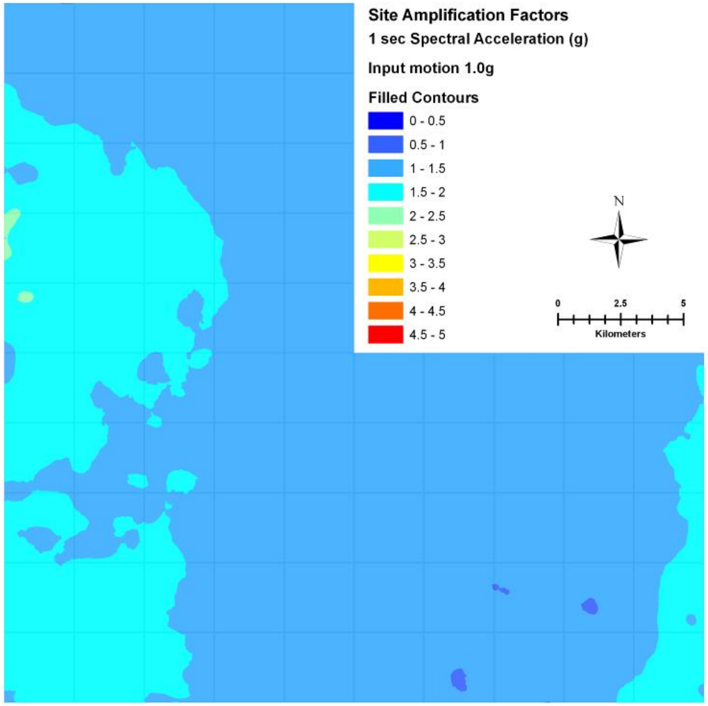

Site Amplification Factors
0.2 sec Spectral Acceleration (g)
Input motion 1.0g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers

1.0 sec SA


Site Amplification Factors
1 sec Spectral Acceleration (g)
Input motion 0.01g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers


Site Amplification Factors
1 sec Spectral Acceleration (g)
Input motion 0.05g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers


Site Amplification Factors
1 sec Spectral Acceleration (g)
Input motion 0.4g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers


Site Amplification Factors
1 sec Spectral Acceleration (g)
Input motion 1.0g
Filled Contours
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 3.5
3.5 - 4
4 - 4.5
4.5 - 5
N
0
2.5
5
Kilometers

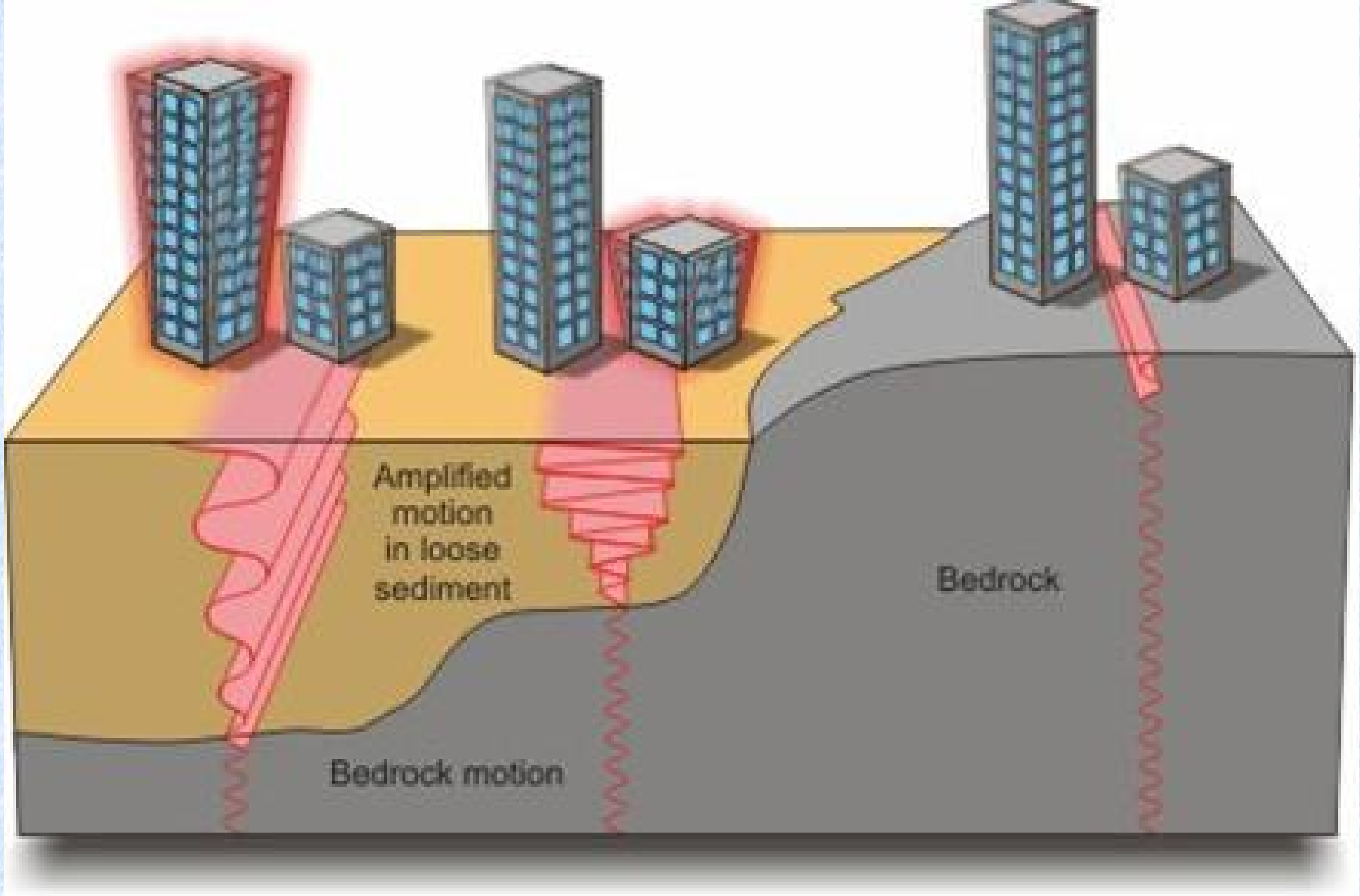
Summary of Results

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 impeedance contrast between bedrock and soil cap.

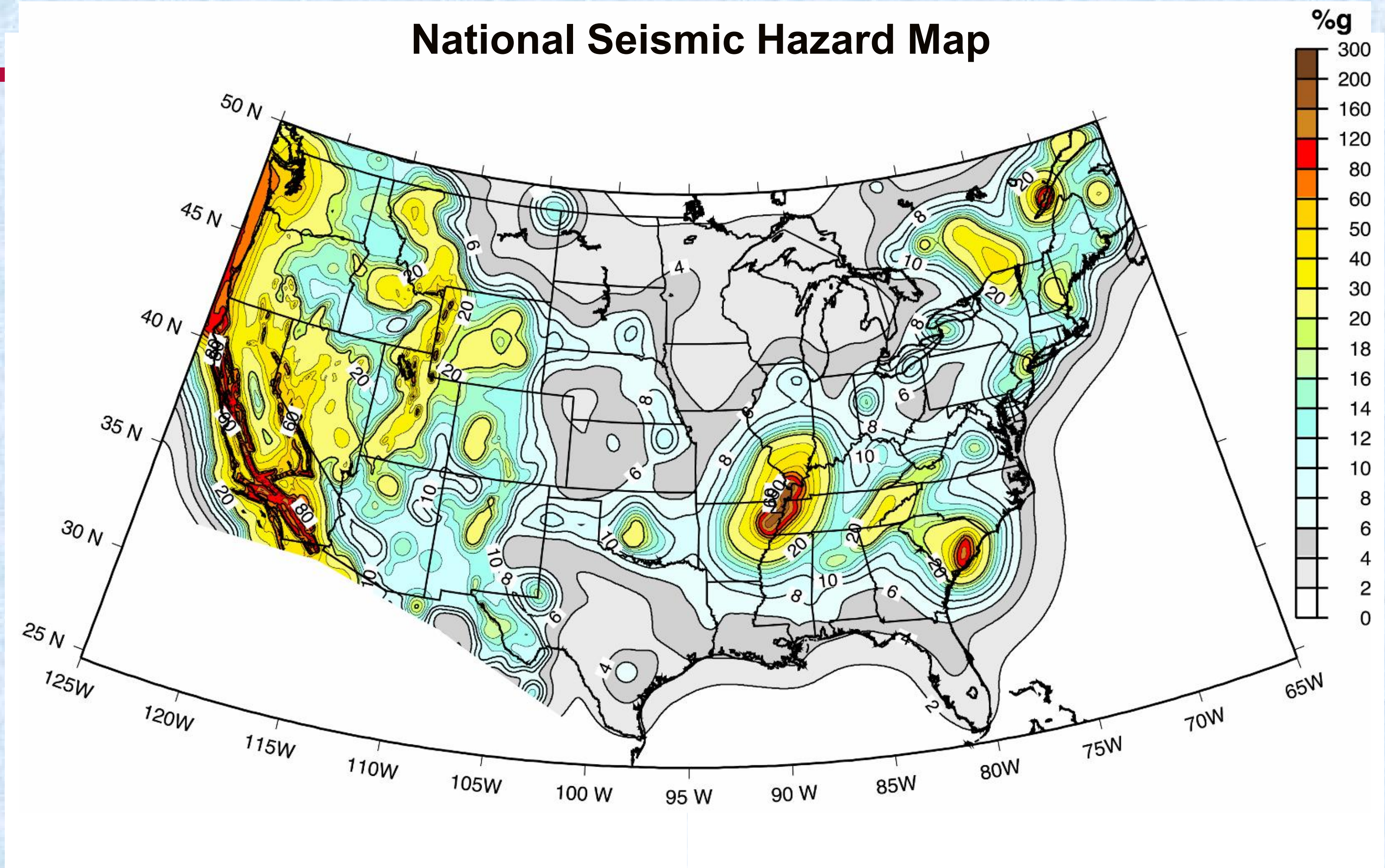
Step 8

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"

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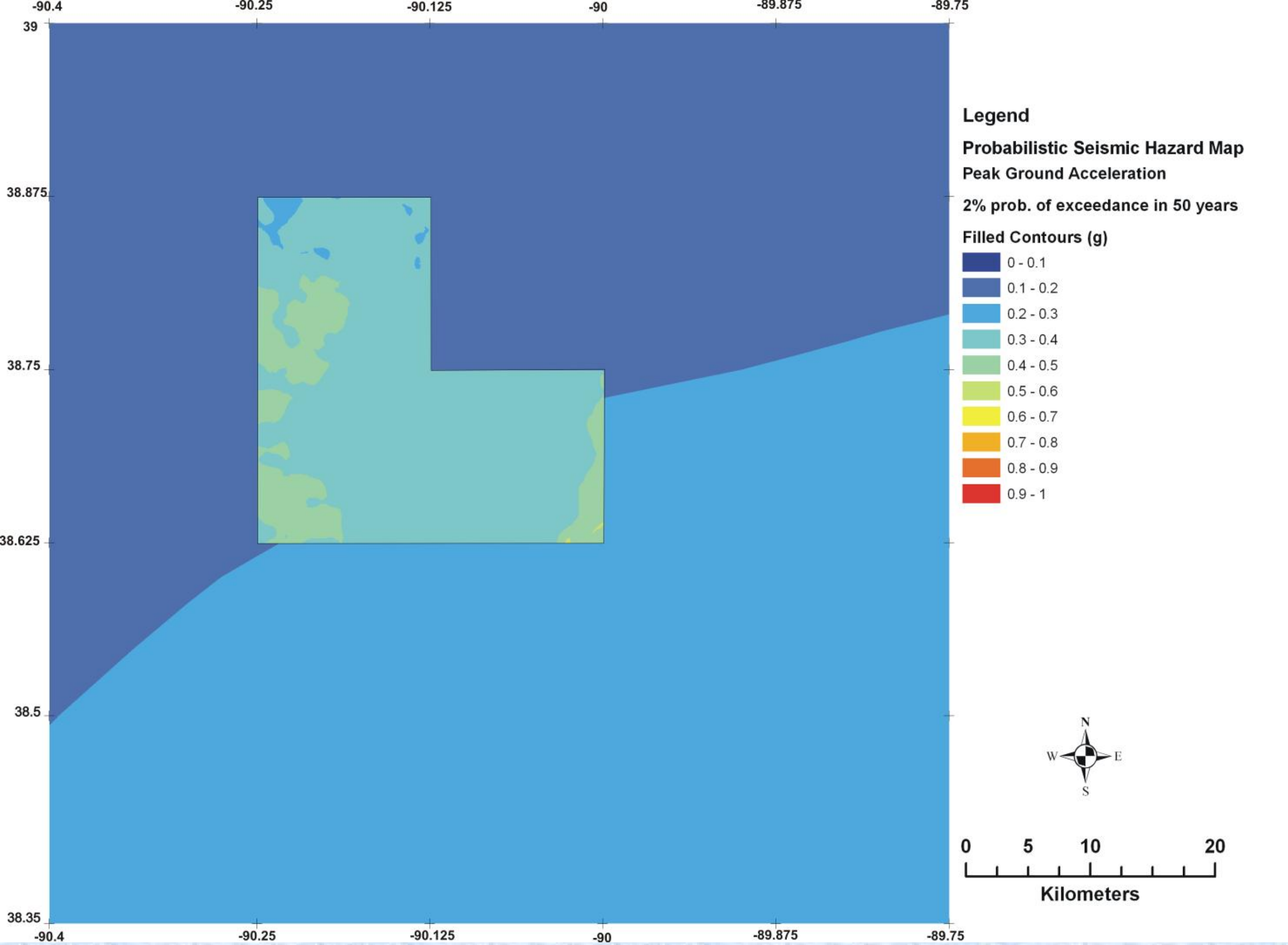
Urban Seismic Hazard Maps (Memphis and St Louis)

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

Missouri S&T study study vs USGS National Map (2002)

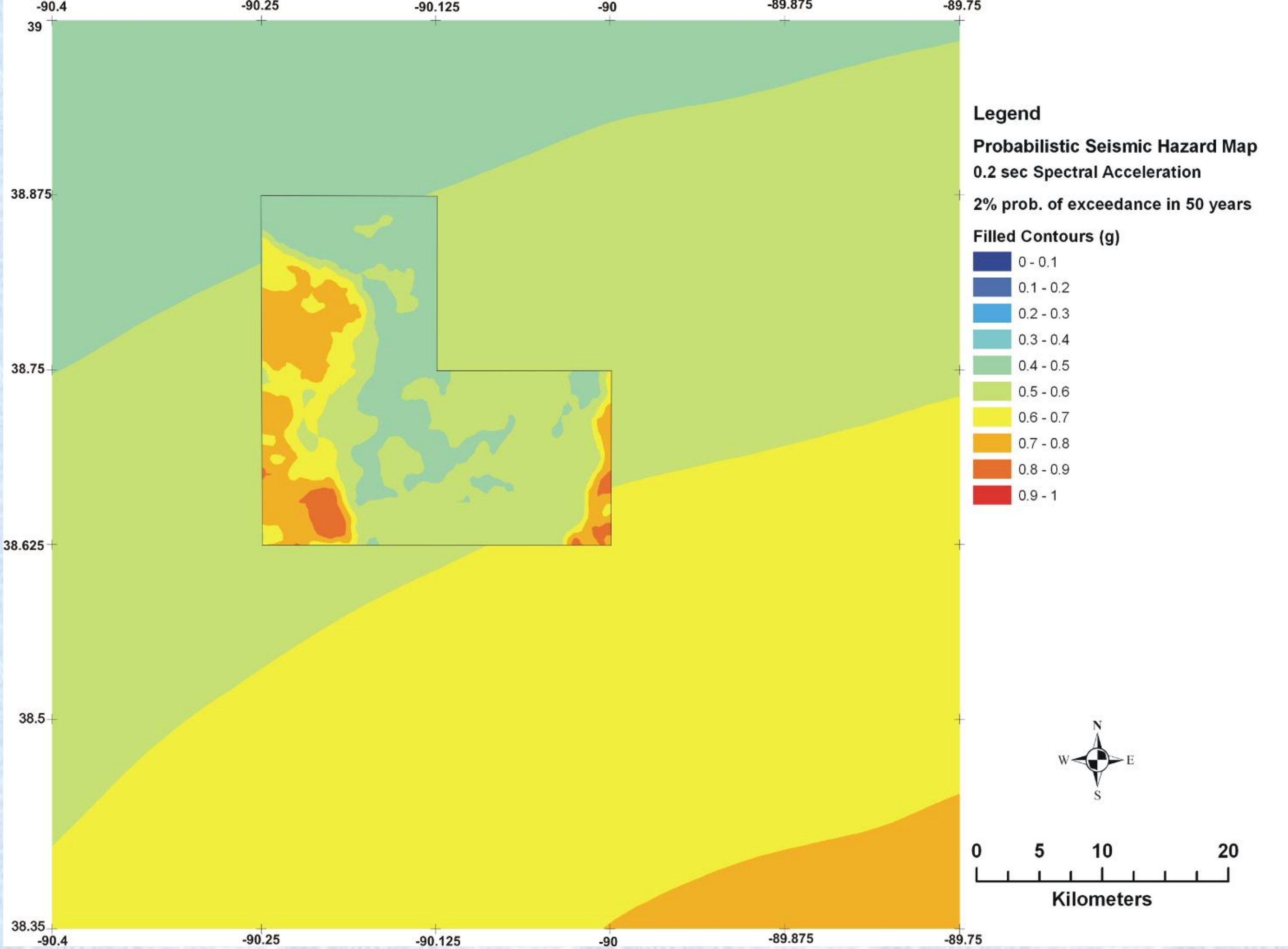


As much as 300% greater accelerations in loess

As much as 200% greater accelerations in alluvium

PGA (g)		Alluvium	Loess
2%-in-50	Max	0.383	0.547
	Min	0.267	0.245
	Mean	0.333	0.423

Missouri S&T study vs USGS National Map (2002)



As much as 200% greater accelerations in loess

As much as 20% lower accelerations in alluvium, locally.

0.2 sec SA		Alluvium	Loess
2%-in-50	Max	0.783	0.965
	Min	0.407	0.422
	Mean	0.511	0.750

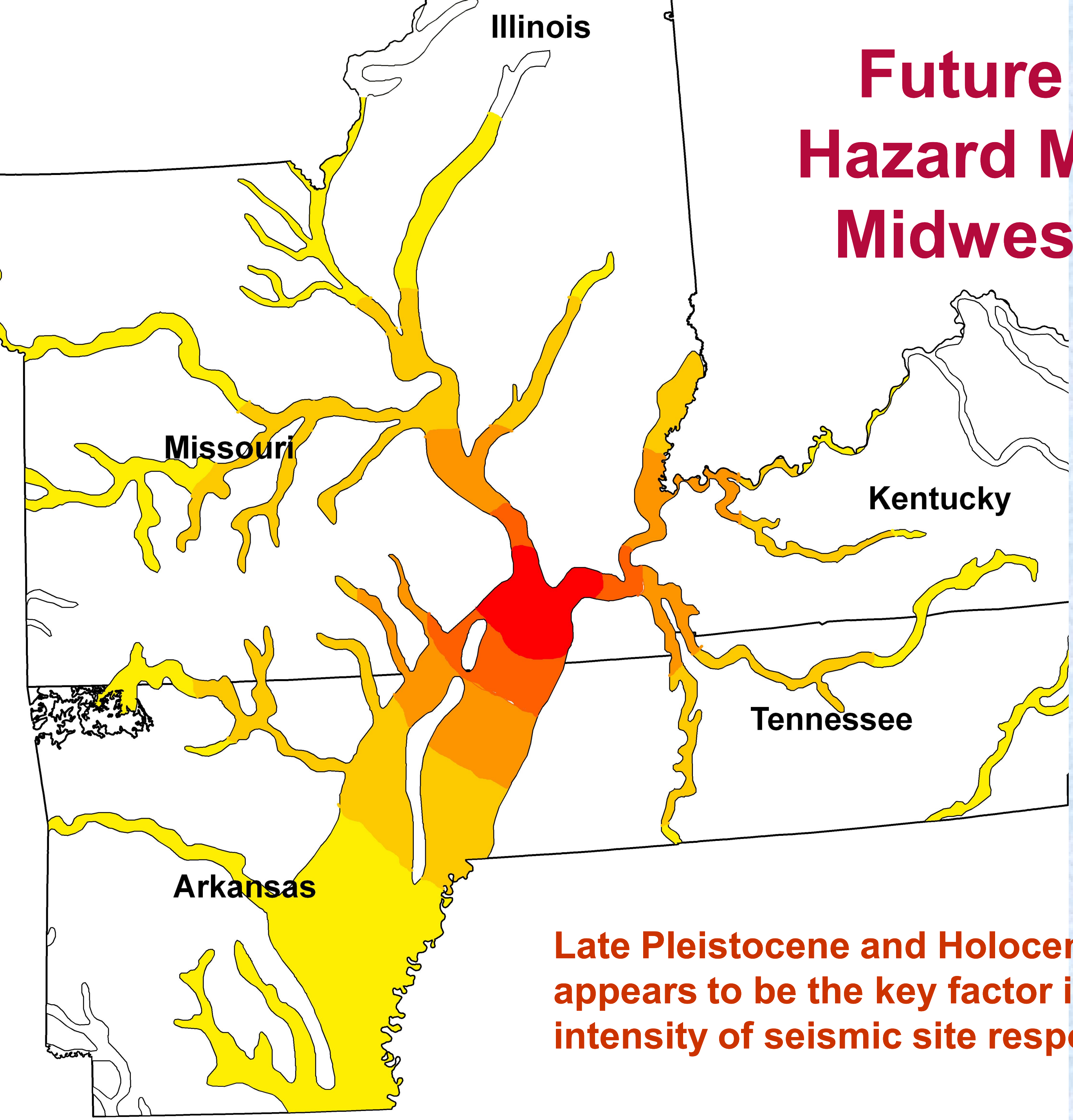
Summary: Shaking intensity is controlled by the underlying geology

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.

Future Seismic Hazard Map for the Midwestern USA



Late Pleistocene and Holocene Alluvial thickness appears to be the key factor in controlling local intensity of seismic site response

Future Work - 1

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).

Future Work - 2

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.

Acknowledgments

Grants from the U.S. Geological Survey-National Earthquake Hazard Reduction Program and the USGS Central-Eastern U.S. office (Rob Williams and Eugene Schweig)

Illinois State Geological Survey (Robert Bauer)

Central United States Earthquake Consortium

Missouri DNR-Division of Geology and Land Survey

Professor Chris Cramer at the University of Memphis

St. Louis Area Earthquake Hazard Mapping Program Technical Working Group and

Phyllis Steckel, RG – SLAEHMP TWG facilitator

Dr. Deniz Karadeniz, Dr. Jae-won Chung, Ece Karadeniz, and David J. Hoffman of the Missouri S&T research team

This lecture will be posted at: http://web.mst.edu/~rogersda/nmsz/