Distinguishing between Data Uncertainty and Natural Variability in Geotechnical Databases

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Geotechnical Site Characterization
GIS Virtual Geotechnical Databases (VGDB)

• Geodata layers:
  – Geological mapping
  – Geophysical information/data
  – Geotechnical subsurface information
  – Water wells and geoenvironmental monitoring wells

• General Purpose: enables any sort of spatial analysis, and serves as a predictive model of subsurface conditions

• In this study, the VGDB provided fundamental input data for regional assessment of earthquake hazards, ground shaking intensity, and liquefaction potential, that can be released to the public
St. Louis Metro Area

- 4,200 km²
- 29 quadrangles
- river valleys
- glacial outwash
- dissected loess
- covered uplands
1.2. St. Louis Metropolitan Area

• STL includes the confluences of the Mississippi, Missouri, Illinois, and Meramec Rivers.

The area consists of: 1) floodplains along these rivers; and 2) 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.
The study area consists of 29 USGS 7.5 minute Quadrangles in Missouri and Illinois.
1.3. Purpose of Study

A). Creation of seven GIS Geodata layers underlying the St. Louis Metro Area

a) Collect and Input the existing geodata in ArcGIS v9.1 format:
   - 1) Surficial geology
   - 2) Loess thickness
   - 3) Bedrock geology
   - 4) Borehole information

b) Gather existing 5) Shear wave velocity (Vs) data, and assess soil amplification (@ to NEHRP site classes),

c) Interpolate 6) Groundwater elevations and 7) Depths-to-bedrock, using geostatistics in ArcGIS v 9.1
2-1. Data Sources for Surficial Geologic Map

Data Sources (16):

Hardcopy formats:
- US Geological Survey (USGS)

GIS format:
- Illinois State Geological Survey (ISGS)

MoDGLS presently compiling 1:24,000 scale maps of specific high interest quadrangles, for this study
## 2.1. Surficial Geologic Mapping

### Time Scale Interpretation

<table>
<thead>
<tr>
<th>Time Scale</th>
<th>Interpretation</th>
<th>This study</th>
<th>Missouri (Schultz, 1993)</th>
<th>Illinois (ISGS publications)</th>
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<tr>
<td></td>
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<td>Symbol</td>
<td>Symbol</td>
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<td>Residuum</td>
<td>R</td>
<td>R</td>
<td>Residuum</td>
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<td></td>
<td>Alluvium</td>
<td>Qa</td>
<td>Qa</td>
<td>Alluvium</td>
</tr>
<tr>
<td></td>
<td>Alluvial or colluvial fans</td>
<td>c(f)</td>
<td>Qa</td>
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<tr>
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<td>Alluvium (backswamp, channel-fill or overbank)</td>
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<td>Qa</td>
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<td></td>
<td>Alluvium (point bar or channel)</td>
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<td>Colluvium</td>
<td>Qp(py)</td>
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<td>Holocene over Pleistocene</td>
<td>Alluvium over lake deposits</td>
<td>c/e</td>
<td>c(e)</td>
<td>Cahokia Fm over Equality Fm</td>
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<td>c(c)-e</td>
<td>c(c)-e</td>
<td>Cahokia-Clayey or Equality Fm</td>
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<td>Lake sediment (slackwater)</td>
<td>Qtd or e</td>
<td>Qtd</td>
<td>Terrace deposits</td>
</tr>
<tr>
<td></td>
<td>Outwash</td>
<td>Qtd</td>
<td>Qtd</td>
<td>Terrace deposits</td>
</tr>
<tr>
<td></td>
<td>Loess</td>
<td>Qtd</td>
<td>Qtd</td>
<td>Terrace deposits</td>
</tr>
<tr>
<td>Pleistocene (Wisconsinan over Illinoian)</td>
<td>Loess over ice-contact drift</td>
<td>Ql(pr/pl-h)</td>
<td>pr/pl-h</td>
<td>(pr) over Pearl Fm-Hagarstown M</td>
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<tr>
<td></td>
<td>Loess over outwash</td>
<td>Ql(pr/pl)</td>
<td>pr/pl</td>
<td>(pr) over Pearl Fm</td>
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<tr>
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<td>Loess over till over lake sediment</td>
<td>Ql(pr/pb)</td>
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<td>Till and ice marginal sediment</td>
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<td>Qt</td>
<td>Qt</td>
<td>Till</td>
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<td>Paleozoic</td>
<td>Qt</td>
<td>Qt</td>
<td>Karst</td>
</tr>
<tr>
<td></td>
<td>Bedrock</td>
<td>Qt</td>
<td>Qt</td>
<td>Bedrock</td>
</tr>
</tbody>
</table>
Surficial geologic units
2-1. Compiled Surficial Geologic Map

Vector data model
2.2. Loess Thickness Map

• Loess (windblown silt) Thickness affects:
  1) soil development and productivity
  2) the management of soils for engineering and other uses:
     (1) slumping and slope stability
     (2) foundation failures
     (3) erosion and piping

Loess (Peoria/Roxana Silts) in STL area were deposited during the last glaciation cycle (Wisconsin Episode)
LiDAR imagery gathered on 1.6 m posting, showing an approximately 4 square mile portion of the Florissant Karst region in the northernmost portion of St. Louis County, overlain by a blanket of loess.
This image was derived from bare earth LiDAR datasets of St. Louis and St. Charles Counties, MO, which illustrates the striking density of sinkholes developed in the underlying St. Louis Limestone.
Structural and stratigraphic control in karst

- Karts features are commonly developed along faults and shears, regular systematic joints, and along bedding horizons.
2.2. Data Sources for Loess Thickness Map

Data Sources (5):

Hardcopy formats:
- USGS (1952)
- Goodfield’s thesis (1965)

GIS format: ISGS (2007)

Problems with disparaging scales:

- St. Charles and Jefferson counties in Missouri mapped at small scale of 1:2,500,000 (where the contour lines mapped in much less detail),
- Illinois portion and St. Louis County/City at larger scales of 1:24,000 to 1:100,000
Drawbacks

• When the bedrock surface is uniform there is little uncertainty in the calculations. However, large variations in the data within small distances cause problems in the predictions.

• The loess deposits mantling 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.
2.2. Compiled 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
2.3. Data Sources for Bedrock Geology Map

Data Sources (5):

- Hardcopy formats:
  - Missouri Department of Natural Resources (MoDNR-DGLS)

- GIS format: USGS, ISGS

1. Harrison (1997), scale 1:100,000
2. Whitfiled (2002), scale 1:24,000
3. Stincomb and Fellows (2002), scale 1:24,000
4. Middendorf and Brill (2002), scale 1:24,000
5. Kolata (2005), scale 1:500,000
2.3.1 Map Scale Matching Problems

- Joining problems: 100K and 24K scale map boundaries do not match
2.3.1. Map Scale Matching Problems

- Possible Solutions:
- For mismatching boundary area, editing another 24K map boundaries instead of 100K map.
<table>
<thead>
<tr>
<th>ERA</th>
<th>SYSTEM</th>
<th>SERIES</th>
<th>FORMATION</th>
<th>SYMBOL</th>
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<td>Holocene</td>
<td>Alluvium</td>
<td>Qal</td>
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<td></td>
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<td>Terrace Deposit</td>
<td>Qt</td>
</tr>
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<td>Tertiary</td>
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<td>Unconformity</td>
<td></td>
</tr>
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<td></td>
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<td>Grover Gravel</td>
<td>Tg</td>
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<td></td>
<td></td>
<td>Pleistocene</td>
<td>Terrace Deposit</td>
<td>Qt</td>
</tr>
</tbody>
</table>

**Stratigraphic Correlations**

from various sources, and,
Symbols used for Mapped Units
2.3 Compiled Bedrock Geology Map

Vector data model
## 2.4. 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>
<th>Item</th>
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<tr>
<td><strong>Missouri</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bedrock</td>
<td>2338</td>
<td>Depth to bedrock, Bedrock type</td>
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<tr>
<td></td>
<td>Corelog</td>
<td>729</td>
<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></td>
<td>Material</td>
<td>2330</td>
<td>Description of soil material</td>
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<tr>
<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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<tr>
<td></td>
<td>Water Observation</td>
<td>961</td>
<td>Depth to groundwater</td>
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<td>Site</td>
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<td><strong>Illinois</strong></td>
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<td>Highway Log</td>
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<td>Description of soil material</td>
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<td>Highway Engineering</td>
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<td>Standard Penetration Test (SPT) N-value</td>
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<td>Highway Head Log</td>
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<td>4817</td>
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</table>
Weathering profiles engender uncertainty in bedrock depth.
Common interpretive errors

- A major disadvantage of drive sampling is the small diameter of the cutting shoe.
- For example, the SPT procedure cannot recover clasts > 1.375” diameter, which often leads to erroneous interpretations of “bedrock” contacts or “drilling refusal.”
The tip of the cone penetrometer senses out ahead of itself as it induces a local bearing failure of the soil it passes through.

The tip resistance recorded by the instrument is an average across this tip influence zone.

Therefore, caution should be exercised when evaluating insitu strength parameters for horizons less than about 8 inches (20 cm) thick.
2.4. Borehole Locations

- Data Sources:
  - MoDNR-DGLS
  - ISGS

- Note Data Gaps in eastern St. Charles and Jefferson counties
4.1 Geospatial Prediction of the Groundwater Table in the STL Metro area

- Application: important consideration in engineering and environmental decision making; for
  - waste disposal sites
  - natural hazards, such as shaking-induced soil liquefaction and lateral spreads.
4.1.1. General Specifications of Groundwater Table

- The physical position of the groundwater table is generally influenced by the following criteria:
  1) mimics the general shape of the land surface
  2) is approx. equal to the ground elevation in streams,
  3) the depth-to-groundwater tends to be deeper in elevated uplands
4.1.2 Previous Methods Used to Predict the Position of the Groundwater Table

- Manually contouring groundwater levels taken from monitoring wells

- Multiple(or simple) linear regression for each aquifer unit (Andres and Martin, 2005; O’Hara and Reed, 1995; Sepulveda, 2003; Williams and Williamson, 1989)

- Geostatistical methods
  - Kriging (Dunlap and Spinazola, 1980)
  - Cokriging (Hoeksema et al., 1989)
4.1.3. Interpolation Method

1) Kriging

• (Ordinary) Kriging is a geostatistical method that estimates unsampled values by calculating the spatial relationship between sampled values and distances from the sampled locations. The estimated values at these unsampled locations is obtained by:

\[ X^*(u_0) = \sum_{i=1}^{n} \lambda_i X(u_i), \quad \sum_{i=1}^{n} \lambda_i = 1 \]

where \( X^*(u_0) \) = estimated value at location, \( u_0 \); \( X^*(u_i) \) = sample value at location \( u_i \); \( \lambda_i \) = weighting factor
When the ground surface (2\textsuperscript{nd} variable) has high correlation with groundwater table (1\textsuperscript{st} variable), Cokriging can improve the estimate by considering a bounding ground surface (2\textsuperscript{nd} variable).
Cokriging

- The cokriging equation is usually expressed as:

\[ X^*(u_0) = \sum_{i=1}^{n} \lambda_{X_i} X(u_{X_i}) + \sum_{k=1}^{m} \lambda_{Y_k} Y(u_{Y_k}), \]

\[ \sum_{i=1}^{n} \lambda_{X_i} = 1 \quad \text{and} \quad \sum_{k=1}^{m} \lambda_{Y_k} = 0 \]

where \( X^*(u_0) \) = estimated value at location, \( u_0 \), \( X(u_{X_i}) \) = sample value located at \( u_{X_i} \), \( Y(u_{Y_k}) \) = covariable value located at \( u_{Y_k} \), \( \lambda_{X_i} \) = weighting factor at \( X(u_{X_i}) \), and \( \lambda_{Y_i} \) = weighting factor at \( Y(u_{Y_k}) \).
Profile of Groundwater Table (W) with and without considering the ground surface (G) (Hoeksema et al., 1989)

- Estimated W not concerning G
  Using kriging

- Estimate W concerning G while Constraining W=G
  Using cokriging
Kriging and Cokriging

• Advantages
  1) it is an exact interpolator at measured data points
  2) it uses the information from data points surrounding the point of estimation by incorporating the autocorrelation structure of the data
  3) it has the ability to estimate the reliability of the map data (standard error) at unmeasured sites, between the data points

• Disadvantages
  1) It can over- or under-estimate (less accurate) the results in river valleys, where there is a lower density of water wells.
  2) Results may vary with different models (spherical, exponential, etc.)
Cross Validation

• Cross validation: the method of analysis and its respective parameters:

1) mean error (ME)

2) root-mean-square error (RMSE)

3) kriged mean standardized error (MSE)

4) kriged root-mean-square standardized error (RMSSE).

\[ r_{ui} = X^* (u_i) - X (u_i) \]

\[ ME = \frac{1}{N} \sum_{i=1}^{N} r_{ui} \approx 0 \]

\[ RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} r_{ui}^2} \quad \text{Minimum} \]

\[ MSE = \frac{1}{N} \sum_{i=1}^{N} \frac{r_{ui}}{\sigma_{ui}} \approx 0 \]

\[ RMSSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \frac{r_{ui}^2}{\sigma_{ui}^2}} \approx 1 \]

where \( X^* (u_i), X(u_i), r_{ui}, \) and \( \sigma_{ui} \) are the estimated value, the observed value, the error (residual), and the standard deviation of the estimation error respectively at points, \( u_i. \)
4.1.5a. Input DATA for Modeling Groundwater Table

The Input Data in this study (3,621 data points):

- 1) 1,052 well logs were obtained from the Missouri and Illinois Geological Surveys, which was collected between January 1959 and December 2005
- 2) 469 artificially interpolated data (about 1 km apart) along the major river channels; extracted from 24k DRGs and 10 m DEMs, and stitched together,
  - in order to prevent overestimates in the low-lying floodplains
- 3) 2,100 points in the upland streams originated from hydrography digital line graph (DLG).

- It is assumed that groundwater table elevation = surface ground elevation in conditions 2) and 3)
4.1.5a. Input DATA for Modeling Groundwater Table
4.1.5b. Relationship between Ground Surface and Groundwater Elevations

- This graph shows the correlation between the groundwater table and ground surface elevations.
- The black line shows the best fit correlation line.
4.1.5c. Relationship between Ground Surface and Groundwater Elevations, using Cokriging

- The physical correlation between the slope of the ground surface and that of the underlying water table was actually verified in this study (see previous figure).

- This would suggest that cokriging should be employed to estimate the elevation of groundwater table, because it provides a more realistic fit.
Uncertainty of Reported Groundwater Levels
Measurement errors very common

(1) - the observed level in a simple standpipe records to combined inflow from the upper unconfined layer and the lower semi-confined layer.
(2) - the true groundwater level in the upper unconfined aquifer.
(3) - the true groundwater level of the lower semi-confined aquifer, within the silty clay aquiclude.
(4) - where groundwater level would typically be recorded, at the time of drilling (atod).
(5) - the reported groundwater level in an active water well, subject to conical drawdown.
Uncertainty of Groundwater Level

- **Measurement Discrepancies** observed in the Mississippi River valley around St. Louis

  - Properly installed monitoring wells with sealed collars generally indicate gwt @ ~ 0.7 m below ground surface
  
  - GWT levels recorded in adjacent geotechnical borings typically record depths between 2.7 and ~ 4 m (Bauer at ISGS, 2011)
  
  - Missouri Geological & Land Survey Maps typically cite gwt depth of ~ 4.5 m (Gaunt et al., 2009)
3. The groundwater table is subject to natural variability over time and space (e.g., the St. Louis metro area)

Changes in potentiometric surface (in feet) from 1980-85; (after Kohlhase, 1987)
Subsurface data with reported groundwater levels

- Physiographic divisions and distribution of data points
Interpolation of Groundwater Table

- Conceptual profiles of groundwater table with and without surface topography and inferred data points
Nine geomorphic provinces were grouped to assess uncertainties in determining physical properties for various geological terrains, such as alluvial or loess/colluvial covered uplands.
Linear Regression Model

• **Advantages**
  – It can easily produce the prediction map, considering the changes of geomorphic shapes and averaging the trend.

• **Disadvantages**
  – 1) it is NOT an exact interpolator at measured data points
  – 2) it does not produce the reliability of the map data (standard error) at unmeasured sites, between the data points
Beware of GIS-driven predictions of groundwater levels

- Most geoenvironmental and geohydrology studies employ simple kriging to estimate groundwater levels, using available well records.
- Cokriging that includes dissected ground surface as a covariable usually provides a more realistic prediction.
- Note that multiple regression overestimates in the uplands and underestimates the true values beneath the flood plains.
4.2. Preliminary Maps of Water Table Elevation

- The position of the groundwater table was interpolated, based on 1,052 well logs and 2,569 artificial data points along drainages.

- Using 1) Kriging and 2) Cokriging in ArcGIS geostatistical analysis.
Kriging Map of Groundwater Table Elevation

Raster data model

Standard Error Map Using Kriging
Predicted Groundwater Elevations

- Produced using co-kriging
- Exhibits excellent correlations with groundwater table in dissected loess-covered uplands
3) Cross-Validation Results

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Kriging</th>
<th>Cokriging</th>
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</thead>
<tbody>
<tr>
<td>ME</td>
<td>-0.2375</td>
<td>-0.3730</td>
</tr>
<tr>
<td>RMSE</td>
<td>5.2750</td>
<td>4.1020</td>
</tr>
<tr>
<td>Kriged MSE</td>
<td>-0.0233</td>
<td>-0.0615</td>
</tr>
<tr>
<td>Kriged RMSSE</td>
<td>1.0440</td>
<td>1.0060</td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>0.9270</td>
<td>0.9570</td>
</tr>
</tbody>
</table>

- Cross validation of cokriging results in
  - Kriged RMSSE of 1.0060 (≈ 1.0)
  - Correlation coefficient of 0.957 (≈ 1.0), compared with the regular kriging analyses.

- This suggests that cokriging produces slightly better estimates and smaller uncertainties in the predicted values at reference locations than did kriging.
5.1. Depth-to-Bedrock (Thickness of Surficial Materials)

- **Depth-to-Bedrock:**
  - Provides some guidelines for mapping the bedrock geology

- **Applicable to**
  - 1) assess the amount and distribution of rock quarries;
  - 2) conduct hydrologic and/or environmental investigations;
  - 3) conduct geotechnical investigations (or other land-use applications).

- Also valuable for predicting potential seismic-risk areas, because sites on thick sequences of unconsolidated sediments are usually more prone to magnification of seismic energy.
5-1. Previous Methods Commonly Employed to estimate Bedrock Elevations (or Depth-to-Bedrock)

- Manually contouring known bedrock elevations
  (Herzog et al., 1994)

- Statistical methods
  - Spline (Grimley and Denny, 2004)
    - for bedrock elevation
  - Kriging (Gao et al., 2006)
    - for depths-to-bedrock
  - Cokriging (Nyquist et al., 1996)
    - for bedrock elevation
  - Subdividing map area and apply different modeling techniques
    (Hasenmueller, 2006)
    - for depths-to-bedrock
5.1. Problem 1: Interpolating the Bedrock Surface

- In undulating terrain, the bedrock surface often presents a complex feature, shaped by numerous erosional and deformational events.

- The interpolation in rugged terrain often leads 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.
5.1. Problem 2: Interpolating Bedrock *depth* v.s. Bedrock *elevation*

- Which interpolation method comes closest to estimating the actual bedrock surface?
  - A) Interpolating Depths-to-bedrock?
  - or
  - B) Interpolating Bedrock elevation?
5.1. Objectives

• Interpolating bedrock surface between data points.
  – 1) Depths-to-bedrock using the *kriging technique*
  – 2) Bedrock elevations using the *cokriging technique*

• Comparing methods 1) and 2), and ascertaining which model best fits the actual data.
## 5.1. Input Data

**Data Sources:**
1. MoDNR-DGLS
2. ISGS
3. USGS
4. MS&T

<table>
<thead>
<tr>
<th>Location</th>
<th>State</th>
<th>Geotechnical borings to bedrock surface</th>
<th>Seismic reflection</th>
</tr>
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<tbody>
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<td>Not piercing</td>
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5-1. Uplands vs. Floodplains depth-to-bedrock data in **STL**

- **Data sources:** 8,260 subsurface data points (from subsurface data)
- **Surficial Material Thickness (m) in STL**
  - Uplands: 0~44 m (12 +/- 8, \( \mu \) +/- \( \sigma \))
  - Floodplains: 0~48 m (23 +/- 12)
- **Bedrock surface is deeper beneath the floodplains**
5-1. Trends observed between Uplands and Floodplains

- In the upland areas, bedrock elevations appear more-or-less proportional to the ground surface elevation.
5-2. Proposed Interpolation Method 1

- The map areas were divided into:
  - 1) Uplands, and
  - 2) Floodplains,

because bedrock elevations in these areas exhibited contrasting distributions
5-2. Proposed Interpolation Method 2

- Interpolation and corresponding uncertainties between sampled sites were computed:
  - 1) for the depth-to-bedrock using kriging
  - 2) for the bedrock elevation using cokriging
5-3. Procedure of Interpolating

- 5-3-1 The Depths-to-Bedrock, using kriging
- 5-3-2 The Bedrock elevations, using cokriging
5-3-1 Procedure of Interpolating Depths-to-Bedrock

- 1) Approximating (kriged) bedrock surface using borings that pierced the bedrock interface

After Hasenmueller (2006)
5-3-1 Procedure of Interpolating Depth-to-Bedrock

- 2) Approximating minimum (kriged) bedrock surface, using all borings, even those which do not pierce the bedrock interface.
3) Of these two approximations, my model was programmed to select the *deeper bedrock surface*, which appears to be more accurate.
Procedure employed to interpolate bedrock depths

- **A** - Interpolated bedrock surface using borings piercing the bedrock surface only
- **B** - Interpolated bedrock surface using all borings
- **C** - Final estimated bedrock surface, selecting the deeper bedrock surface
5-3-1 Sample Distribution and Kriging Map of Depth-to-Bedrock

Depth-to-Bedrock (m)
Kriging Map of Depth to Bedrock

The greatest uncertainties exist in floodplains.

Input data = 12,600 points
5-3-2 Interpolating Bedrock Elevation

- **Cokriging Top-of-Bedrock Elevations**
  - **Primary variable:**
    - Bedrock elevation data
  - **Secondary variable:**
    - Ground elevation (500m×500m grids) extracted from DEM
Mississippi River channel

- Peoria and Roxana Silt - loess
- Cahokia Formation (Cc, Cs)
- Glasford formation - till
- Henry Formation (h)

Only one boring piercing the bedrock
Regressional modeling of bedrock profile

- Interpolation was employed between adjacent regressional models of complex curvature because of the small number of borings penetrating the bedrock along the Missouri River channel.
Proposed Procedure of Bedrock depth in the Floodplains

- Proposed Procedure: polynomial regression model
Reevaluation of Bedrock depth in the Floodplains

- Profiles of bedrock positions, interpolated by the kriging and the regressional models
5-3-2 Sample Distribution and Cokriging Map of Bedrock Elevation

Standard error map
5-4 Comparison of Actual Data and Depths-to-Bedrock and Bedrock Elevation Maps

- Estimates of Depths to Bedrock
  - Depths-to-bedrock model: Between 4m and ~42m in uplands and 1m to ~47m in the floodplains.
  - These ranges generally agree with previously reported data and the data points (0 to 44m, and, 0 to 48m, respectively).
  - Bedrock elevation model: Depths of bedrock up to ~60m of were estimated. These are considerably higher than the actual data (<10m) in most of the problematic areas (e.g., ridgetops in Jefferson County, Missouri, and along river bluffs in Jersey County, Illinois). This erroneous estimate of bedrock elevation may be attributed to smoothly underestimating and overestimating bedrock elevations in unsampled portions of hilly areas and alluvium valleys, respectively.
Conclusions

• Significant Uncertainties exist in most Geodatabases: Assessing uncertainty is a key aspect in developing realistic spatial estimation methodologies. As in years past, this will require considerable engineering judgment.

• Uncertainties:
  – In bedrock depth: the weathered zone and/or isolated blocks are often reported as “bedrock” in boring logs.
  – In groundwater levels: too often based on limited observations, erroneous methods of measurement, and wildly varying water depths reported at any given site over time. Upwards of 85% of this data may be erroneous.
  – In Vs30 data: an uneven distribution of Vs30 data exist over the study area, due to contrasting geomorphic provinces and methods of measurement.

• Proposed Interpolation Procedures:
  – Bedrock depth: realistic interpolation models can be constructed by using 1) ordinary kriging for the uplands, and 2) regression-kriging for the floodplains.
  – Groundwater levels: cokriging produces more realistic estimates, using the spatial relationship between groundwater elevations and land surface.
  – Vs30: NEHRP soil site categories assigned based on the surficial geologic units, both categories (e.g., C to D), and the percentage of Vs tests within the site classes per geologic unit.