Shear-Wave Velocities and Derivative Mapping For the Upper Mississippi Embayment

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Abstract

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During the past two decades, University of Kentucky researchers have been acquiring seismic refraction/reflection data, as well as seismic downhole data, for characterizing the seismic velocity models of the soil/sediment overburden in the central United States. The dataset includes densely spaced measurements for urban microzonation studies and coarsely spaced measurements for regional assessments. The 519 measurements and their derivative products often were not in an organized electronic form, however, limiting their accessibility for use by other researchers. In order to make these data more accessible, this project constructed a database using the ArcGIS 9.1 software. The data have been formatted and integrated into a system serving a wider array of users. The seismic shear-wave velocity models collected at various locations are archived with corresponding x-, y-, and z-coordinate information. Flexibility has been included to allow input of additional data in the future (e.g., seismograms, strong ground-motion parameters and time histories, weak-motion waveform data, etc.). Using the completed database, maps of the region showing derivative dynamic site period (DSP) and weighted shear-wave velocity of the upper 30 m of soil ($V_{30}$) were created using the ArcGIS 9.1 Geostatistical Analyst extension for examination of the distribution of pertinent dynamic properties for seismic hazard assessments. Both geostatistical and deterministic techniques were employed. Interpolation of $V_{30}$ data yielded inaccurate predictions because of the high lateral variation in soil layer lithology in the Jackson Purchase Region. As a result of the relatively uniform distribution of depths to bedrock, the predictions of DSP values suggested a high degree of accuracy.

Keywords: GIS, geodatabase, kriging, shear-wave velocity, dynamic site period

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Shear-Wave Velocity Database and Derivative Mapping
For the Upper Mississippi Embayment

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THESIS

David M. Vance

The Graduate School

University of Kentucky

2006
SHEAR-WAVE VELOCITY DATABASE AND DERIVATIVE MAPPING
FOR THE UPPER MISSISSIPPI EMBAYMENT

THESIS

A thesis submitted in partial fulfillment of the
requirements of the degree of Master of Science in the
College of Arts and Sciences
at the University of Kentucky

By

David M. Vance

Director: Dr. Edward W. Woolery, University of Kentucky
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2006

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For Laura Leigh Vance
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1.0 Introduction

1.1 The Dataset

During the last two decades, researchers at the University of Kentucky have collected numerous seismic velocity data, especially in the vicinity of the New Madrid Seismic Zone, including western Kentucky, southeastern Missouri, northeastern Arkansas, northwestern Tennessee; and the Wabash Valley Seismic Zone, located in southern Indiana and Illinois. Additional microzonation data have been collected in the Kentucky cities of Paducah, Henderson, Louisville, and Maysville (Figure 1).

In addition to seismic velocity, the data provided the depth to bedrock at each site, thicknesses of overlying soil layers, and location coordinates. The weighted average shear-wave velocity of the upper 30 meters (V30) of soil/bedrock, calculated according to the 1997 National Earthquake Hazard Reduction Program (NEHRP) provisions (BSSC, 1997), were included in some of the studies from which the data were taken. The V30 values were manually calculated and added to the dataset in which they were not originally included. Dynamic site periods (DSP) were also included in some of the original studies and calculated for studies in which they were not originally included. Other associated data from the original sources, such as the site name, site classification, average sediment and bedrock velocities, elevation, soil type, collection date, and topographic map name were also included.

The purpose of these data is to characterize and model the soil/sediment overburden in the central United States in order to determine the ground-motion site effects during an earthquake. Flexibility in the database is built in for future additions of new data and data types. For this project, the Jackson Purchase Region of western Kentucky (Figure 2), because of its increasing development, particularly in the vicinity of Paducah, and because of its proximity to major geologic structures and seismically active zones, was selected for derivative mapping.

The seismic risk to engineered structures in the central United States necessitates the research to characterize earthquake site effects in the region. Several seismic zones are present in the central United States, including the Eastern Tennessee Seismic Zone, the South Carolina Seismic Zone, the Giles County Seismic Zone (in Virginia), the Anna, Ohio, Seismic Zone, the Northeastern Kentucky Seismic Zone, and the New Madrid Seismic Zone, which dominates the overall seismic hazard. The influence of local geologic/soil conditions on the amplitude, frequency content, and duration of any size earthquake ground motion is referred to as “site
effects.” Site effects may have a more profound influence on ground motions than the magnitude in areas with a thick sediment overburden (Street et al., 1997). Ground-motion parameters can be either amplified or attenuated by the dynamic soil properties (e.g., sediment velocity, natural period), the subsurface geometry at both one-dimensional local and two- and three-dimensional basin scales, and surface topography. Only one-dimensional local site effects were considered in this project. Neglecting material damping and scattering effects, for example, as a seismic wave passes into a region of low impedance from a region of high impedance, the resistance to motion decreases and the wave amplitude must increase to maintain energy conservation.

The effect of near-surface geometry is evident in the case of a site with dynamic soil properties remaining the same, changing only the thickness (H) of the sediments above bedrock. According to the equation for the frequency of the soil, \( f_s = \frac{\beta}{4H} \), where \( \beta \) = shear-wave velocity, an increase in thickness of the sediments results in a decrease in frequency. The dynamic site period (DSP), the period at which the fundamental mode of resonance occurs, is the inverse of the frequency and is used to design structures with fundamental periods that differ from the DSP, avoiding in-phase resonance between the structure and soil column and therefore minimizing damage during an earthquake (Street et al., 1997).

The weighted shear-wave velocity of the upper 30 m of soil/bedrock (\( V_{30} \)), as calculated in accordance with the 1997 NEHRP Recommended Provisions for Seismic Regulations for New Buildings (BSSC, 1997), is used for site classification of the more poorly consolidated sediments of the near-surface soils. These site classifications can then be used to calculate site-dependent seismic coefficients, which are used to produce soil amplification maps (Street et al., 2001).

Derivative maps generated using the Geostatistical Analyst extension of ArcGIS 9.1 are useful for providing DSP estimates across the study area. Researchers can use the maps for examination of the distribution of the values, which would otherwise be impossible without sample locations at every point.

To support ongoing earthquake site-effects research, the objectives of this project were to 1) retrieve seismic velocity data collected by University of Kentucky researchers from various media (e.g., journals, theses, dissertations, reports), 2) digitize the data and organize by project, 3) use methods to interpolate pertinent dynamic properties for seismic hazard assessments (i.e., \( V_{30} \) and DSP values), and 4) interpret the resultant derivative maps.
Figure 1. Geographic distribution of the 519 sample locations contained in the database.
Figure 2. The Jackson Purchase Region of western Kentucky (highlighted in red). The lower figure shows the distribution of sample locations in the study area. The concentration of sample sites in McCracken County centers around the Paducah urban area and the samples were collected by Harris (1992). The remaining samples were collected by Street et al. (1997).
1.2 Data Accessibility

The usefulness of 519 seismic velocity soundings has been limited because of the inaccessibility of the data. Often, the data did not exist in electronic form, requiring researchers to spend time and energy locating the data in published reports, theses, and journal articles. The existence of data was sometimes unknown. In addition, examination of the data to identify trends and to derive useful information was often difficult because there was no easy way to plot the data for spatial representation and perform rapid manipulation of the dataset. Therefore, another goal of this project was to digitize the database in a manner that would allow queries and spatial representation in map form. Specifically, this digitization provides a view of the sample site distribution and allows statistical analyses that would be overly cumbersome to perform by hand.

1.3 The GIS Database

For this project, the ArcGIS version 9.1 suite of applications, including ArcCatalog, ArcMap, and ArcToolbox, developed by the Environmental Systems Research Institute (ESRI), was selected because of its comprehensive database management tools, geostatistical analysis capabilities, and wide acceptance in the scientific community. Dowdy (1998) compared ArcGIS to various other GIS software packages, such as Rockworks, TerraSoft, and MapInfo.

The data in this study were organized in the geographic database, or geodatabase, by name of researcher and study area location. This design allows a user to examine data and perform operations on data from specific areas, since future studies will likely focus on a particular area rather than an entire region. The data may easily be reconfigured to allow operations on the full dataset, however. The personal geodatabase, feature dataset, and feature classes were created directly in ArcCatalog with no data initially contained within. Data were entered into the geodatabase manually by transfer from other digital sources or directly from printed sources. Each dataset from a single source forms a point feature class and all feature classes are included in a single-feature dataset to enforce a common spatial reference. This ensures that all data points will be projected at the appropriate locations on the map. The feature dataset and all included data are stored in a personal geodatabase (Figure 3). Metadata were created to document the source, quality, and other information related to the data using the template available in ArcCatalog.
1.3.1 Application 1: ArcGIS Functionality

ArcGIS 9.1 includes the Geostatistical Analyst extension, which was used to demonstrate two applications of ArcGIS functionality: specifically, derivative maps of the mean dynamic site period (DSP) and weighted shear-wave velocity of the upper 30 meters of soil ($V_{30}$) distributions. Geostatistical Analyst provides tools such as histograms, Voronoi maps, Quantile-Quantile (QQ) plots, trend analysis, and semivariogram/covariance clouds for exploratory spatial data analysis (ESDA), which is used to examine the data for trends and to identify data outliers. Application of these tools assists the parameter selection process, resulting in more accurate prediction maps. An explanation of the available tools for ESDA was included in this text, and comparisons between interpolation methods were made using the root-mean-square (RMS) and other prediction error measurements, also provided in Geostatistical Analyst, to identify the most accurate method.

1.3.2 Application 2: Interpolated Maps

Although geophysical knowledge of an entire area such as the Jackson Purchase is desirable, the collection of such an enormous amount of data is both logistically and fiscally unrealistic. For this reason, interpolation of the data between data points over the study area, using deterministic and stochastic methods based on the limited samples already collected,
allows prediction of values of a particular geophysical property at any given location with a finite amount of accuracy. Deterministic methods, such as splines, apply mathematical functions to the dataset for the interpolation process. Stochastic methods, such as kriging, also use mathematical functions but include geostatistical methods as well to account for the randomness inherent in geologic and data collection processes. Therefore, stochastic methods provide measures of accuracy and a level of confidence in the predictions. The methodology for producing such interpolated maps is documented and then demonstrated using the real dataset from the Jackson Purchase area.

2.0 Geographic Information System (GIS)

In addition to having human and organizational components, a geographic Information system (GIS) is defined as:

An integrated collection of computer software and data used to view and manage information about geographic places, analyze spatial relationships, and model spatial processes. A GIS provides a framework for gathering and organizing spatial data and related information so that it can be displayed and analyzed (ESRI GIS Dictionary).

The utility of GIS spans multiple industries, and GIS has been used to integrate the operations of organizations in more powerful ways than in the past. Specifically, in the past organizations relied on hard copies of information and data in the form of compact disks and paper files, often resulting in duplication of work. The use of shared geodatabases has reduced operation time and costs and prevented the duplication of work already accomplished.

2.1 Development of Geographic Information Systems

The historical development of GIS is based in a variety of disciplines and is well documented (Foresman, 1998). Developments in the separate fields of geographic information systems and spatial data analysis and their convergence can be traced beginning in the 1950s and 1960s. One expression of this convergence is found in the ArcGIS Geostatistical Analyst extension of ArcGIS 9.1. The Geostatistical Analyst extension is used for application of statistical methods to datasets and production of derivative maps.

The ArcGIS software package was developed by the Environmental Systems Research Institute (ESRI) with capabilities for handling geoprocessing, database management, and digital
cartographic projects. The release of ArcGIS 8 in 1999 introduced ArcCatalog, ArcMap, ArcToolbox, and several extensions for data viewing and manipulation (ArcCatalog), projection and analysis (ArcMap), conversion and processing (ArcToolbox), and utilization for various specific applications (extensions such as Geostatistical Analyst, Spatial Analyst, and 3D Analyst). Subsequent versions such as 8.1, 8.3, 9.0, and 9.1 build upon previous versions to enhance functionality, usability, and performance.

2.2 Applicability

Data collected by researchers at the University of Kentucky existed primarily in paper form (e.g., journals, theses, dissertations, reports), making the data difficult to access and manipulate. Often, the existence of previously collected data was overlooked. ArcGIS provides an efficient platform for the storage and display of data and offers the Geostatistical Analyst extension and accompanying Exploratory Spatial Data Analysis (ESDA) environment for data analysis. The GIS technology was used to enhance seismic research efforts by organizing data in digital form and creating derivative maps of dynamic soil properties for regional assessment of seismic hazard.

2.2.1 ArcGIS (ArcCatalog, ArcMap, ArcToolbox, and Extensions)

In this project, the ESRI ArcGIS 9.1 software package was used, and the Geostatistical Analyst extension of version 9.1 was of particular interest for its ability to apply statistical methods to spatial datasets and to determine trends, identify outliers, and produce derivative maps of a given attribute. The various interpolation methods also yield measures of uncertainty.

2.2.2 Geostatistical Analyst

*Exploratory Spatial Data Analysis (ESDA)*

ESDA is a component of Geostatistical Analyst that is used to apply statistical methods to the dataset. The available tools include histograms, Voronoi maps, normal and general QQ plots, trend analysis, semivariogram/covariance clouds, and crosscovariance clouds. Each method assists in identification of data outliers, trends in the data, spatial autocorrelation, and data distribution.
Histograms

Histograms show the frequency distribution of the data in one variable and calculate summary statistics such as the count, minimum and maximum values, mean, median, standard deviation, skewness, kurtosis, and first and third quartiles. Carr (1995) defined these terms that describe histogram characteristics.

Voronoi Maps

Voronoi maps are composed of polygons, each of which contains a sample point, and are constructed so that any given point within the polygon is closer to the sample point in that polygon than any other sample point on the map. Statistics calculated within Voronoi maps allow the identification of local smoothing, local variation, local outliers, and local influence. There are eight types of maps that can be produced with this tool, including simple, mean, mode, cluster, entropy, median, and standard deviation. Four of the eight types of Voronoi maps were used in this project and are described below. Table 1 shows the functional purpose of each type of Voronoi map.

- **Simple**: The value assigned to a cell is the value recorded at the sample point within that cell.
- **Mean**: The value assigned to a cell is the mean value that is calculated from the cell and its neighbors.
- **Cluster**: All cells are placed into five class intervals. If the class interval of a cell is different from each of its neighbors, the cell is colored gray to distinguish it from its neighbors.
- **Standard Deviation**: The value assigned to a cell is the standard deviation that is calculated from the cell and its neighbors.
## Table 1. Various aspects of a dataset examined using Voronoi maps (ESRI, 2006).

<table>
<thead>
<tr>
<th>Functional category</th>
<th>Voronoi statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Smoothing</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td>Mode</td>
</tr>
<tr>
<td></td>
<td>Median</td>
</tr>
<tr>
<td>Local Variation</td>
<td>Standard deviation</td>
</tr>
<tr>
<td></td>
<td>Interquartile range</td>
</tr>
<tr>
<td></td>
<td>Entropy</td>
</tr>
<tr>
<td>Local Outliers</td>
<td>Cluster</td>
</tr>
<tr>
<td>Local Influence</td>
<td>Simple</td>
</tr>
</tbody>
</table>

**Quantile-Quantile (QQ) Plots**

A cumulative distribution for a dataset is produced by ordering the data and producing a graph of the ordered values versus cumulative distribution values calculated as \((i - 0.5)/n\) for the \(i\)th ordered value out of \(n\) total values (the percent of the data below a value) (ESRI, 2006). Normal QQ plots, used to determine if the data are normally distributed, are constructed by plotting data values with standard normal values that have equal cumulative distributions, as shown in Figure 4 (ESRI, 2006). General QQ plots, used to examine the similarity of distributions between two datasets, are constructed by plotting values from one dataset with values from a second dataset that have equal cumulative distributions (Figure 5).
Figure 4. Construction of a normal QQ plot, which is used to examine the distribution of a dataset (ESRI, 2006).
Figure 5. Construction of a general QQ plot, which is used to compare distributions of two datasets (ESRI, 2006).

Trend Analysis

To identify trends for mapping or removal, the trend analysis tool is used to view the data in a three-dimensional graph. The samples are plotted by location on the x, y plane. The z plane shows the values of the measured attribute of interest. The values are then projected on both the x, z plane and the y, z plane as scatter plots. Polynomial curves are fitted through the scatter plots to show trends. Additional features allow rotation of the graph and sample points to isolate directional trends, change of perspective, change of size and color of points and lines, removal of planes and points, and selection of the order of polynomial used to fit the scatter plots (Figure 6).
Semivariogram/Covariance Clouds

The semivariogram/covariance cloud, defined by Schabenberger and Gotway (2005), is used to examine spatial autocorrelation and identify data outliers and is constructed by plotting the difference squared between the values of two points for a designated attribute as a function of the distance between the pair of points. Thus, one dot on the cloud represents a pair of sample points.

Crosscovariance Clouds

Used to examine spatial autocorrelation between two datasets and to identify spatial shifts in correlation between the two datasets, the crosscovariance cloud is constructed by plotting the empirical crosscovariance for pairs of locations between two datasets as a function of the distance between them.

2.3 Surface Creation Using Interpolation Techniques

Geostatistical Analyst uses a finite set of sample points at known locations to calculate (predict) unknown values at unsampled locations and produce a map showing the distribution of values over an area. A fundamental geographic principle states that samples close together are more alike than samples farther apart. Based on this assumption, Geostatistical Analyst uses two types of interpolation techniques to derive surfaces based on limited datasets: deterministic methods and geostatistical methods. This assumption is often not applicable geologically. Specifically, the Jackson Purchase Region exhibits strong lateral variation in lithology over short distances, which resulted in higher prediction errors associated with the \( V_{30} \) derivative maps. This is attributed to the fact that \( V_{30} \) is calculated based on the thickness of individual soil layers, which vary appreciably over short distances. The DSP values, which are dependent on the total thickness of sediments above bedrock, demonstrated a more uniform distribution, resulting in low prediction errors.
Figure 6. The trend analysis tool, showing distribution, trends, and magnitude of the DSP dataset.
2.3.1 Deterministic Methods

The deterministic interpolation methods can be characterized as global or local, exact or inexact, and are based on either extent of similarity between data points or degree of smoothing. Each method may be considered as a combination of one or more of these characterizations.

Global and Local Interpolators

Global interpolators (global polynomial) utilize the entire dataset when calculating the output surface, whereas local interpolators (inverse distance weighted, local polynomial, and radial basis functions) use search neighborhoods, which are smaller areas within the extent of the entire study area.

Exact and Inexact Interpolators

Exact interpolators (inverse distance weighted and radial basis functions) force the output surface to pass through the sample points, meaning the value of the derived surface is exactly equal to the measured value of the original dataset. Inexact interpolators (global polynomial and local polynomial) calculate values that vary slightly from the measured values, reducing sharp peaks that may occur in the output surface as a result of forcing the surface to pass through the measured sample points.

Extent of Similarity vs. Degree of Smoothing

Interpolators such as inverse distance weighted (IDW) perform interpolations based on the extent of similarity between data points. IDW gives more weight to points closer to the location at which a value is being calculated and gives progressively diminishing weight to points that are farther apart. Radial basis functions (RBF), such as splines, fit a surface through all data points while reducing the amount of curvature of the derived surface between points.

2.3.2 Geostatistical Methods

Geostatistical interpolation techniques involve both mathematical and statistical models. For this reason, these methods can be used to create maps showing the standard error and uncertainty in the prediction surfaces. The ability to produce error and uncertainty surfaces allows the user to attain a level of confidence in the accuracy of the derivative maps and is a distinguishing feature between the geostatistical and deterministic interpolators. Geostatistics is
dependent on the assumption that data are autocorrelated, meaning they are the result of random processes with dependence. The dependence rules are determined during the ESDA process (ESRI, 2006).

The group of interpolation techniques based on mathematical and statistical models is known collectively as kriging. Several varieties of kriging are available in Geostatistical Analyst including ordinary, simple, universal, indicator, probability, disjunctive, and cokriging. Advantages of using the geostatistical techniques include the ability to use semivariogram/covariance clouds, perform transformations, remove trends, and account for measurement error.

**Ordinary Kriging**

Ordinary kriging is modeled by the function

$$Z(s) = \mu + \varepsilon(s)$$

where $\mu$ is an unknown constant mean and $\varepsilon$ is autocorrelated error at location $(s)$ (Figure 7). A constant mean across a large study area is probably unrealistic in most cases, but may be sufficiently flexible to achieve the desired result. Acceptable results are relative and depend greatly on the goals of the researcher.

**Simple Kriging**

The model used in ordinary kriging is also used in simple kriging, but here the mean, $\mu$, is assumed to be known. Previously, when using ordinary kriging $\mu$ was unknown and estimated. Therefore, $\varepsilon$ was also estimated. When $\varepsilon$ is known, it is possible to make better estimations of autocorrelation and to produce more accurate derivative maps.
Figure 7. Ordinary kriging fits an unknown constant mean, $\mu$, to the dataset with autocorrelated random errors, $\varepsilon(s)$. $Z(s)$ is a measured value, $Z$, at location ($s$) (ESRI, 2006).

Universal Kriging

Universal kriging uses a mathematical model similar to the previous two methods. The model used is

$$Z(s) = \mu(s) + \varepsilon(s)$$

where $\mu(s)$ represents a deterministic function, rather than a known or unknown constant mean (Figure 8). The deterministic function is fitted to the data in Figure 8 as a second-order polynomial. Subtraction of the polynomial from the data results in a plot of autocorrelated errors. Universal kriging can be thought of as regression performed on spatial coordinate variables (ESRI, 2006).
Figure 8. In universal kriging, the data are fitted with a deterministic function, $\mu(s)$. Errors, $\varepsilon(s)$, are assumed to be autocorrelated (ESRI, 2006).

**Indicator Kriging**

Indicator kriging is defined by the equation

$$I(s) = \mu + \varepsilon(s),$$

where $\mu$ is an unknown constant and $I(s)$ is a binary variable (ESRI, 2006). This method may be used on binary data or on binary data created by establishing a threshold on a continuous dataset. Otherwise, the procedure is the same as that for ordinary kriging (Figure 9).
Figure 9. Indicator kriging interpolations indicate the probability of a given location having a value of 1, or in the case of a threshold applied to a dataset, the probability of the value at a point exceeding or not exceeding the threshold. Here, the dashed line indicates an unknown mean, $\mu$. The measurement error, $\varepsilon(s)$, is assumed to be autocorrelated. Multiple thresholds can be used to establish primary and secondary indicator variables, and interpolations can then be performed using the cokriging technique (ESRI, 2006).

**Probability Kriging**

The probability kriging method is defined by the equations

$$I(s) = I(Z(s) > c_t) = \mu_1 + \varepsilon_1(s)$$

$$Z(s) = \mu_2 + \varepsilon_2(s),$$

where $\mu_1$ and $\mu_2$ are unknown constants, and $I(s)$ is a binary variable indicating exceedance or nonexceedance of a set threshold. This method is similar to indicator kriging, but uses cokriging rather than regular kriging, with the intent of producing more accurate results. The drawback is the extra estimation needed for autocorrelation of each variable and cross-correlation between datasets, potentially introducing more uncertainty.
**Disjunctive Kriging**

Disjunctive kriging is defined by the function

\[ f(Z(s)) = \mu_1 + \epsilon(s), \]

where \( \mu_1 \) is an unknown constant and \( f(Z(s)) \) is an arbitrary function of \( Z(s) \) (ESRI, 2006). This model can also be written as \( f(Z(s)) = I(Z(s) > c_i) \). The functions available are \( Z(s_0) \) and \( I(Z(s_0) > c_i) \). According to ESRI (2006), disjunctive kriging “requires the bivariate normality assumption and approximations to the functions \( f_i(Z(s_i)) \); the assumptions are difficult to verify, and the solutions are mathematically and computationally complicated.”

**Cokriging**

Cokriging is potentially more powerful than kriging. In addition to the autocorrelation present in the main dataset of interest, information from another dataset is cross-correlated with the variable from the main dataset to achieve greater accuracy. If correlation does, in fact, exist between the two datasets, the resulting output surface should model reality more accurately. If there is no cross-correlation between datasets, the predictions are still made from the autocorrelation present in the original dataset. The risk involved comes from the added parameter estimations, which may introduce more variability, effectively negating any gains made from using the second dataset, possibly wasting the extra effort required to interpolate with more than one dataset.

Ordinary cokriging is defined by the mathematical models

\[ Z_1(s) = \mu_1 + \epsilon_1(s) \]
\[ Z_2(s) = \mu_2 + \epsilon_2(s), \]

where \( \mu_1 \) and \( \mu_2 \) are unknown constants (Figure 10). Each of the kriging methods is also available as a cokriging method; in each case a second dataset is used to achieve greater accuracy.
Similar to ordinary kriging, ordinary cokriging uses a second dataset with positive correlation to the original dataset to achieve greater accuracy (ESRI, 2006).

3.0 Application 1: Shear-Wave Velocity Database

Geophysical data were collected at 519 sites by researchers at the University of Kentucky, including Harris (1992), Al-Yazdi (1994), Higgins (1997), Street (1997), Street et al. (1997), Wood (2000), Lin (2003), Wang et al. (2004), and Street et al. (2005). Seismic-refraction surveys were conducted for the collection of SH-wave velocity data for all studies from which data were included in this database. This was typically accomplished using a seismograph with internal hard drive for signal data storage, connected to two inline spreads of horizontally polarized 4.5- or 30-Hz geophones. Spacing of geophones typically ranged from 2 to 10 m. The geophones detected seismic shear waves generated by an energy source, such as a section (approximately 12 kg) of steel H-pile beam struck horizontally by an approximately 4.5-kg sledgehammer. For maximum energy transmission, the H-pile beam was oriented perpendicular to the spread of geophones and was coupled with the ground surface by placing the edge against an asphalt surface or a prepared slit in the soil. SH-waves were used because the velocities at which they travel are characteristic of the soil medium, whereas P-waves travel
at velocities characteristic of water when generated in water-saturated sediments (Higgins, 1997).

To achieve the best possible signal-to-noise ratio, several strikes by the energy source at one location were stacked upon each other. This method allowed random noise generated by successive hammer blows to be cancelled out by destructive interference while coherent noise was constructively interfered to produce a more robust signal (Rutledge, 2004). In some instances, the hammer impacts were recorded for each side of the energy source and added together to enhance coherent SH-wave signals and to decimate other phases and random noise (Street et al., 1997).

The walkaway method was used, in which a 12- or 48-geophone spread remains fixed while the energy source is systematically struck and moved along a set of predetermined offsets dependent on geologic site conditions. Information gained from this method included velocities and intercepts of head-waves, identification of reflection events and interval velocities, and calculation of thicknesses of soil horizons and depths to bedrock (Street et al., 1997).

3.1 The Dataset and Database Development

The dataset includes seismic velocities, latitude/longitude coordinates, the depth to bedrock at each site, thicknesses of overlying soil layers, weighted-average shear-wave velocity of the upper 30 meters (V30) of soil/bedrock, calculated according to the 1997 NEHRP provisions (BSSC, 1997), site name, site classification, average sediment and bedrock velocities, elevation, soil type, collection date, and topographic map name (Figure 11). The V30 values were manually calculated and added to the dataset in which they were not originally included. Dynamic site periods (DSP) were also included in some of the original studies and calculated for studies in which they were not originally included. Appendix A contains complete tables of all data currently stored in the database.

The current form of the database represents a template in which additional data can be included. New fields can be created and filled, and appropriate relationships established between data fields. The geodatabase (GDB) was created in ArcCatalog from Microsoft Excel files that were imported into the GDB using ArcCatalog’s tools. Each table derived from the Excel files was converted to a feature class and stored in a feature dataset to ensure a common spatial reference. The feature classes were organized according to the researcher and geographic
location of the sites from which the data were collected. Figure 12 shows the process by which a geodatabase is created in ArcCatalog.

Different types of databases can be created in ArcGIS including enterprise (or multiuser) geodatabases and personal geodatabases. Enterprise geodatabases are typically used for handling large amounts of data (databases over 2 GB) in projects requiring multiple users for editing. ArcSDE is required for managing the database, and multiple storage models can be used, including IBM DB2, IBM Informix, Microsoft SQL Server, Oracle, and Oracle with Spatial or Locator. Versioning is supported in the enterprise geodatabase environment, allowing multiple users to edit the database simultaneously. Conflict resolution rules prevent separate users from editing the same feature at the same time in a contradictory manner. The personal geodatabase model is used for handling databases 2 GB or smaller, and is edited by a single user. The Microsoft Jet Engine (Access) is used for database management, and versioning is not supported. The smaller size of the dataset and the intended uses of the database make the personal geodatabase model ideally suited for this project. As the size of the database increases and new types of data are added, such as image files, conversion to the enterprise model may be necessary.

The data that were originally located in various journals, theses, and other hard-copy publications were initially digitized as Excel files and later imported into the GDB. ArcInfo is based on Microsoft Access, however, which can be used to create tables and databases directly. Empty feature classes and feature datasets can be created and placed in a geodatabase using ArcCatalog, and data can be subsequently entered. The choice of method for database creation is subjective, and the most efficient method depends highly on the pre-existing format of the data.

Metadata is defined as “data about data,” and is used to describe the data being stored in the GDB. The purpose of metadata is to provide an efficient way for users to locate desired data and determine the source, usefulness, and quality of the data. Descriptions of data provenance, quality, and purpose were included in the GDB, and standard formats available from ESRI, found in ArcCatalog, provided the template.
Figure 11. The Jackson Purchase sites feature class table in ArcCatalog. See Appendix A for data tables for all sources included in the database.
**Figure 12.** A personal geodatabase is created in ArcCatalog by using menu options. Feature datasets, feature classes, tables, and relationship classes can all be established within the geodatabase.
4.0 Application 2: Derivative Maps of the Jackson Purchase Region

4.0.1 Study Area: Geologic Setting of the Jackson Purchase

Seismic velocity models have been collected at sites throughout the central United States. Using some of the ArcGIS tools available for analyzing data stored in the geodatabase, the Jackson Purchase area of western Kentucky was selected to provide a regional overview of seismic hazard characteristics. The methods used are applicable to other areas in which similar data have been collected. The Jackson Purchase extends east–west from Kentucky Lake to the Ohio River, and north–south from the Ohio River to the Tennessee border. The city of Paducah is the most populous city in the area (population approximately 30,000) and is located adjacent to the Ohio River along the northern boundary of the Jackson Purchase.

Notably, the Jackson Purchase Region represents the northeasternmost part of the Mississippi Embayment. The Mississippi Embayment is a south-plunging syncline whose axis is roughly parallel to the course of the Mississippi River, filled with sediments ranging in age from Jurassic to Quaternary. These sediments overlie Ordovician and Mississippian bedrock (Davis, 1987). In the Jackson Purchase, Cretaceous to Quaternary sediments overlie the Paleozoic bedrock. The generalized stratigraphy of the Jackson Purchase area is shown in Table 2, and the post-Paleozoic sediment formations are described, from oldest to youngest, in Olive (1972):

**Tuscaloosa Formation:** The Tuscaloosa Formation rests unconformably on the Paleozoic bedrock surface and consists of chert gravel sediments and interspersed lenses of chert and silt. This formation was largely derived from rocks of Devonian and Mississippian age.

**McNairy and Clayton Formations:** Rest unconformably on the Tuscaloosa Formation and the Paleozoic bedrock. They are composed primarily of sand and sandy clay. Coal beds are present in some areas near the top of the formation.

**Porters Creek Clay:** Rests conformably on the McNairy and Clayton Formations in most places. The Porters Creek Clay is derived largely from weathered volcanic rocks deposited in nearshore or deltaic environments.

**Wilcox Formation:** Rests unconformably on the Porters Creek Clay and is composed predominantly of interbedded and interlensing sand, clay, and silt.
**Claiborne Formation:** Rests unconformably on the Wilcox Formation and Porters Creek Clay and is composed of quartz sand with lenses of silt and clay deposits.

**Jackson Formation:** Lies unconformably on the Claiborne Formation and is composed of silt and clay with quartz sand lenses.

**Continental Deposits:** Predominantly composed of chert and quartz gravel.

**Loess:** Consists of silt mixed with minor amounts of fine sand.

**Alluvium and lacustrine deposits:** Consist of silt, sand, and gravel and are rarely calcareous.

Other structures located in proximity to the study area include the Reelfoot Rift, a seismically active structure that extends from southwest to northeast and into the Jackson Purchase, and the Rough Creek Graben, a seismically inactive structure that extends east–west through most of western Kentucky. The structural and seismological relationship between the Reelfoot Rift and Rough Creek Graben is not well defined (Wheeler, 1997).

The New Madrid Seismic Zone, which extends from northeastern Arkansas into southeastern Missouri and the Jackson Purchase Region of western Kentucky, is situated within the boundaries of the Reelfoot Rift. Reactivation of the zones of weakness in the vicinity of the rift complex as a result of the regional stress field is thought to be the cause of seismicity in the area (Harris, 1992). Several large earthquakes ranging in magnitude from $m_b, L_g 7.0$ to $m_b, L_g 7.3$ occurred between December 1811 and February 1812 (Nuttli, 1973; Street, 1982). The New Madrid Seismic Zone is the most seismically active intracontinental area in the United States and represents the greatest earthquake threat east of the Rocky Mountains (Nuttli, 1973; Street, 1982; Johnston and Nava, 1985).

Research efforts in the Jackson Purchase Region and surrounding areas have attempted to delineate fault structures to establish controls on the timing of deformation and therefore to better determine locations and rates of seismicity, and to define the geophysical characteristics of the soil/sediment overburden for determining regional seismic hazards. The proximity to New Madrid seismicity, the presence of thick sediment deposits, and the location within the boundaries of the Mississippi Embayment (basin effects) make the Jackson Purchase ideal for emphasizing the objectives of this project.
Several maps were created using the shear-wave velocity database and the Geostatistical Analyst extension in ArcMap. Geostatistical methods were used to examine the data for trends and outliers with histograms, trend analysis diagrams, Voronoi maps, QQ plots, and semivariogram/covariance and crosscovariance clouds. The distribution of data values was examined and maps were generated for the purpose of interpolating characteristics between sites of physical measurements. Diagnostics were performed to determine the accuracy of each method. A summary of each method follows.

The techniques used for identifying trends and data outliers, and for producing derivative maps, depend on the assumption of stationarity in the data. In other words, the samples were collected from a spatially fixed and continuous field and are an incomplete representation of the entire surface. The purpose of this study is to predict with accuracy the magnitude of a particular attribute at all points within the study area.
<table>
<thead>
<tr>
<th>System</th>
<th>Series</th>
<th>Group and Formation</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Holocene and Pleistocene</td>
<td>Alluvium and lacustrine deposits</td>
<td>0 – 56 m</td>
</tr>
<tr>
<td></td>
<td>Pleistocene</td>
<td>Loess</td>
<td>0 – 24 m</td>
</tr>
<tr>
<td><strong>Tertiary and Quaternary</strong></td>
<td>Pliocene and Pleistocene</td>
<td>Continental deposits</td>
<td>0 – 30 m</td>
</tr>
<tr>
<td><strong>Tertiary</strong></td>
<td>Eocene</td>
<td>Jackson Fm.</td>
<td>~122 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Claiborne Fm.</td>
<td>~152 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wilcox Fm.</td>
<td>0 – 107 m</td>
</tr>
<tr>
<td></td>
<td>Paleocene</td>
<td>Porters Creek Clay</td>
<td>20 – 70 m</td>
</tr>
<tr>
<td><strong>Cretaceous and Tertiary</strong></td>
<td>Upper Cretaceous and Paleocene</td>
<td>McNairy and Clayton Fms.</td>
<td>38 – 83 m</td>
</tr>
<tr>
<td><strong>Cretaceous</strong></td>
<td>Upper Cretaceous</td>
<td>Tuscaloosa Fm.</td>
<td>0 – 50 m</td>
</tr>
</tbody>
</table>

**Paleozoic Bedrock**

**Table 2.** Generalized stratigraphy in the Jackson Purchase Region (modified from Olive, 1972).
4.1 Exploratory Spatial Data Analysis (ESDA)

Prior to the application of spatial interpolation methods, exploratory spatial data analysis (ESDA) techniques were applied to better understand the distribution of values contained in the dataset. The tools used for ESDA included viewing histograms, Voronoi maps, normal and general QQ plots, trend analysis, semivariogram/covariance clouds, and crosscovariance clouds. Sample interpolations were performed on the \( V_{30} \) and DSP attributes using both stochastic and deterministic methods. Using the ESDA tools, outliers were identified, trends in the data were determined, and the distribution of the data was examined. Knowledge gained from the suite of ESDA tools was used to select interpolation parameters more accurately and consequently produce more accurate prediction and standard error maps. Figure 13 shows the distribution of sample sites across the study area.

4.1.1 ESDA Applied to the Mean Dynamic Site Period (DSP) Attribute

*Histogram*

To show the frequency distribution of the mean dynamic site period, the histogram tool was used (Figure 14). In this case the “Jackson Purchase sites” layer was chosen and the attribute to be studied was the mean dynamic site period (DSP). The attribute of interest was selected from the dataset, and the resulting histogram is shown in Figure 15. In this diagram, two bars representing DSP values appear to be outliers. Examination of the summary statistics also reveals that the data are not normally distributed. Data distributed normally would be indicated by a skewness value close to 0 and a kurtosis value close to 3. Although normal distribution is not required to perform kriging for prediction maps, normal distribution is necessary for producing quantile and probability maps using ordinary, simple, and universal kriging, according to ArcGIS Desktop Help. Therefore, a log transformation is necessary to normalize the distribution for producing such maps (Figure 16). The resulting histogram shows a skewness value of 0.27127, much closer to 0, and a kurtosis value of 3.4623, closer to the desired value of 3. With the data now normally distributed, there are no obvious outliers in the data. It is evident that the application of a log transformation is needed before performing a kriging interpolation method for quantile and probability maps when using ordinary, simple, and universal kriging. For prediction kriging interpolations, the transformation is not necessary, however.
Figure 13. Distribution of the sample locations in the Jackson Purchase area that were used for the interpolations.
Normal Quantile-Quantile (QQ) Plot

The normal QQ plot is constructed by plotting the quantile values for the dataset versus the quantile values for a standard normal distribution (ESRI, 2006). The normal QQ plot without the log transformation is shown in Figure 17. The plot deviates from the straight line, indicating non-normal distribution. When the log transformation is applied, the resulting plot is closer to a straight line but still shows considerable deviation, particularly between standard normal values of 1.05 to 2.6 (Figure 18). A perfect straight line would indicate perfect normal distribution. Thus, the QQ plot confirms the benefit of applying a log transformation to the DSP data to obtain normal distribution.
Figure 14. The ESDA options are accessible in Geostatistical Analyst.
Figure 15. The histogram of Jackson_Purchase_sites DSP data. No transformation has been applied, and summary statistics are found in the upper right of the window.
Figure 16. The histogram after the log transformation has been applied. The summary statistics reflect the change.
Figure 17. The normal QQ plot with no data transformation.
Figure 18. Normal QQ plot with a log transformation applied to the data.
Voronoi Map

The Voronoi map offers multiple insights into the data. Four of the eight different types of map that may be drawn, including simple, mean, cluster, and standard deviation (StDev), were examined.

The first Voronoi map examined was the *simple* map (Figure 19). The simple Voronoi map shows the extent of each sample point’s local influence. Each polygon reflects the value of the sample point contained within that polygon, and it is possible to see the distribution of values and the areal extent to which the sample points influence the immediate vicinity during interpolation. For example, a concentration of sample points with values between 0.95507 and 1.3487 is found in the vicinity of Paducah (top center of Figure 19). Sparse sample points are found in the upper right corner of the figure (east of Paducah); dominant values are between 1.8995 and 2.67.

In the mean Voronoi map, the value assigned to a polygon is determined by averaging the value of that polygon and its neighbors (Figure 20). The local smoothing effect of this method emphasizes local trends in the dataset.

The cluster Voronoi map is used to identify local outliers (Figure 21). Each of the polygons is placed into five class intervals. If the class interval of a particular cell is different from each of its neighbors, it is colored gray to distinguish it from its neighbors. Figure 16 shows ten outliers across the extent of the map. When choosing parameters for an interpolation, it may be beneficial to remove these outliers in order to prevent unrealistic influence from these anomalies.

The standard deviation map is shown in Figure 22. Values assigned to polygons are standard deviations calculated from a polygon and its neighbors. From the resulting map, it is possible to examine local variation among the data. It is clear that in areas with sparse sample points there is greater variation in the data values, indicating spatial autocorrelation in the dataset. Examination of the Voronoi maps indicates a trend in the DSP values. In general, the values are higher in the northeast and southwest, and lower in the intervening areas. This information is useful when defining a search neighborhood. Specifically, the search neighborhood was elongated northeast to southwest in order to make predictions based on real measurements that were likely to share similar values.
Figure 19. The simple Voronoi map shows that a single sample point has greater local influence where sample locations are sparse. Areas of high sample-point density show less local influence from a single sample point.
Figure 20. The mean Voronoi map. The value assigned to each polygon is calculated by averaging the sample value with those of neighboring polygons. The smoothing effect emphasizes local trends in the data.
Figure 21. The cluster Voronoi map. Each of the values of the sample points is placed into one of five bins. If the value of a polygon is placed into a bin different from that of its neighbors, the polygon is shown in gray. These sample points are identified as local outliers.
Figure 22. The standard deviation Voronoi map. Values are calculated as standard deviations between a sample location and its neighbors, allowing local variation to be identified.
**Semivariogram/Covariance Cloud**

The semivariogram is a plot of the difference squared, \((x_1-x_2)^2\), between two points as a function of the distance between them (ESRI, 2006). The term autocorrelation refers to the correlation of a variable with itself, as measured at different locations. For instance, if positive spatial autocorrelation exists for a given variable, then the magnitude will be more similar at locations closer together than locations measured farther apart (Schabenberger et al., 2005). If the data are autocorrelated, the difference squared should increase as the distance between a given pair of points increases. In choosing the lag size and number of lags, it is general practice to choose values that, when multiplied together, equal about half the greatest distance between a pair of points (ESRI, 2006).

Construction of a semivariogram of the mean dynamic site periods demonstrates directional influences. In Figure 23, the strongest autocorrelation is apparent when the search direction is oriented 45°. This fact has implications regarding the selection of search direction when performing interpolations. During that process, the search neighborhood can be set to preferentially examine adjacent points in the orientation identified from examination of the semivariogram.

The covariance cloud shows the variance between a pair of data points plotted as a function of distance between the two points. Each pair is represented by one red dot on the covariance graph. Figure 24 shows that there is good covariance in the DSP data, which is necessary for accurate interpolation.

**General Quantile-Quantile (QQ) Plot**

The formula for calculating dynamic site period, \(4H/V\), indicates dependence on the depth to bedrock variable, \(H\). For this reason, the general QQ plot is shown with the distribution of the mean dynamic site period quantiles compared to the distribution of depth-to-bedrock quantiles. The result is close to a straight line. The values exceeding approximately \(1.5 \times 10^{-2}\) continue the trend, though DSP data beyond this point predominantly correspond to equal bedrock depth values. The correlation between the two variables is evident from this graph (Figure 25). Correlation of two datasets as demonstrated by the general QQ plot indicates cokriging may be the best-suited interpolation technique. As discussed in later sections, this proved accurate.
Crosscovariance Cloud

When using the cokriging method, the crosscovariance cloud tool can be used to examine the local spatial correlation between two datasets (ESRI, 2006). Figure 26 shows that the crosscovariance of the DSP and bedrock depth datasets remains constant for pairs of data points at increasing distances when the search direction is oriented approximately 45°, indicating the presence of spatial correlation between the two datasets. As with kriging, cokriging assumes the data are spatially correlated. The crosscovariance cloud confirms this assumption.
Figure 23. The semivariogram cloud shows the difference squared between the values of a pair of data points as a function of the distance between them.
**Figure 24.** Covariance cloud of the DSP values showing covariance of a pair of points as a function of the distance between them.
Figure 25. General QQ plot of DSP and bedrock depth data.
4.2 Stochastic Methods

Also known as geostatistical methods, stochastic methods use both mathematical and statistical methods for interpolation and provide measures of uncertainty in the results (ESRI, 2006). Using the Geostatistical Analyst toolbar, the Geostatistical Wizard function is chosen. The input data is selected as “Jackson Purchase sites” and the attribute to be interpolated is the mean dynamic site period (DSP) (Figure 27). In the Methods menu, the interpolation options are listed. Note that a description of each selected method is given to the right of the Methods menu. For the geostatistical methods, the Ordinary Kriging model is the simplest and requires the fewest parameter choices. Each additional parameter that must be selected requires additional estimation, thus potentially introducing more error into the final output surface. Therefore, it is beneficial to select the kriging method that requires the fewest choices of parameters, unless there is sufficient knowledge to select the parameters accurately. Each of the other kriging methods is a derivation of the ordinary kriging model and require more parameter decision-making.

The dynamic site period is calculated according to the equation

$$T_{DSP} = 4H/V$$

where $H$ is the thickness of soil overburden above bedrock, $V$ is the weighted-average seismic shear-wave velocity of the combined soil layers, and $T_{DSP}$ is the dynamic site period. From this equation, it is evident that the DSP is directly proportional to the soil thickness, $H$. Also, it may be assumed that there is a trend in the data that generally follows the distribution of bedrock depth, though the coefficients of the polynomial that would describe the trend are unknown, accompanied by random autocorrelated errors in measured values. Therefore, the universal cokriging model was chosen as the test method for interpolation of DSP values. The universal kriging interpolation technique is examined in detail, and the results of the remaining methods are subsequently discussed and compared.
Figure 27. Cokriging is selected as the interpolation method. The DSP and bedrock depth attributes of the Jackson_Purchase_sites feature class are selected as the input datasets.
4.2.1 Universal Cokriging

The procedure chosen for interpolating DSP values across the study area is the universal cokriging method, defined by two equations,

\[ Z_1(s) = \mu_1(s) + \varepsilon_1(s) \]
\[ Z_2(s) = \mu_2(s) + \varepsilon_2(s) \]

where \( Z(s) \) is any given point to be interpolated, \( \mu(s) \) is the deterministic function defining the unknown trend in the data, and \( \varepsilon(s) \) is the random autocorrelated error associated with a measured sample point. The first equation represents the first dataset, the dynamic site periods, and the second equation represents the depths-to-bedrock (or soil overburden thicknesses) dataset. Each dataset is actually an attribute of the “Jackson Purchase sites” dataset.

To begin the interpolation process, cokriging is chosen as the method of interpolation using the DSP and bedrock depth attributes of the Jackson Purchase dataset. No transformation is selected for either dataset since normal distribution is not necessary for this type of interpolation, and the order of trend is left as constant (Figure 28).

The “detrending” tool is then used to identify and remove trends (Figure 29). Two options are available for detrending. The first is presented as the “Standard Options,” in which the search neighborhood can be selected as 100 percent global, 100 percent local, or any combination of the two. The global search neighborhood uses the entire dataset, whereas the local search neighborhood uses a subset of data values, limiting the influence of points used for the detrending calculation to those located within a defined area around a given location. A color ramp is calculated and a map displaying the defined search neighborhood is drawn. If more than one dataset is being examined, detrending options may be selected separately for each dataset. For this interpolation, detrending combinations were examined for both datasets and were set at 50 percent global and 50 percent local, which resulted in the lowest error values. Figure 30 shows the “Advanced Options” parameters, available where parameters may be set to perform more precise detrending.
Figure 28. Based on information gained from the ESDA process, the universal cokriging method is selected and the type of output surface to be produced is a map showing predicted values across the study area based on measured values from a limited number of sample locations.
Figure 29. The detrending tool standard options.
Figure 30. The detrending tool advanced options.
In modeling the semivariogram and covariance, parameters are selected by default by the Geostatistical Wizard, each optimized according to the input dataset (Figure 31). These parameters include the range, partial sill, nugget, lag size, and number of lags, which describe the semivariogram model and may be entered manually. When viewing the semivariogram model, the curve fitted to the plotted points levels out at a particular distance. The distance at which the curve begins to flatten out is the range. Points within the range are autocorrelated, whereas points beyond the range are not autocorrelated. In theory, the value of the semivariogram at zero separation distance is zero. As a result of measurement errors, however, the semivariogram value at infinitely small separation distance is usually greater than zero. This is referred to as the nugget. The sill is defined as the value on the y-axis corresponding to the range on the x-axis. The partial sill is then defined as the sill minus the nugget. Construction of the semivariogram involves placing the data into bins of similar values. This is done to reduce the number of points displayed in the semivariogram plot, making the necessary calculations manageable. The lag size determines the size of the bins. Lag size must be chosen carefully, because small-scale variation may be masked by a lag size that is too large, whereas a lag size that is too small may overly smooth the results. Both the semivariogram and covariance clouds can be viewed. A search direction may be defined if directional influences are suspected in the data.

The final selection to be made is a function to define the semivariogram and covariance. Functions available include circular, spherical, tetraspherical, pentaspherical, exponential, Gaussian, rational quadratic, hole effect, K-Bessel, J-Bessel, and stable. The semivariogram/covariance model can be defined by one function, or a combination of up to three functions. After examining the fit of the curves to the semivariogram and the resulting error values, it was determined that the addition of the spherical and exponential functions produced the lowest prediction errors.

The covariance of the dataset was also examined (Figure 32). In the covariance cloud, the covariance is plotted as a function of distance, so data that are closer together should show higher covariance.
Figure 31. Modeling the semivariogram/covariance.
Figure 32. Modeling the covariance.
Search neighborhoods may be defined for both datasets (Figure 33). Parameters to be selected include the number and minimum number of neighbors used, shape type, and details concerning the orientation, shape, and size of the search neighborhood. A preview of the sample points and search neighborhood, and a preview of the output surface can be viewed. In the preview of the search neighborhood, any point on the map may be selected to show which sample points will be included in the calculation of the predicted value at that point. The x- and y-coordinates, number of neighbors, and predicted value at a given location are displayed.

Cross-validation completes the model-fitting process. Multiple options are available for viewing plots of predicted versus measured values (Figure 34), error versus measured values (Figure 35), standardized error versus measured values (Figure 36), and a QQ plot of standardized error versus normal values (Figure 37). A table consisting of the coordinates of each measured sample point along with statistics associated with each point, including measured and predicted values, error, standard error, standardized errors, and normal values, results. In addition, measures of interpolation accuracy are provided in the form of statistics of the prediction errors. These statistics are used to assess and compare the accuracy of one output surface to another.

When cross-validation is complete, a summary of the method and selected parameters is displayed (Figure 38). The resulting derivative map is shown in Figure 39. The new output surface layer is added to the basemap. Summary information and a legend are shown in the map’s table of contents. A prediction standard error surface can be produced showing spatially the relative uncertainty in the predictions. A discussion of the results is provided in the following chapter.
Figure 33. Definition of the search neighborhood for dataset 1. A unique search neighborhood may be defined for dataset 2.
Figure 34. Cross-validation involves the interpretation of prediction error statistics. Shown is the predicted versus measured values plot.
**Figure 35.** Plot of error versus measured value. The more accurate the predictions, the closer the points should plot to the line.
Figure 36. Plot of standardized error versus measured value.
Figure 37. Plot of standardized error versus normal value QQ.
Figure 38. Prior to generation of the output surface, the Geostatistical Wizard displays a summary of the parameters selected for interpolation.
Figure 39. The output surface showing distribution of DSP values. See Appendix B for interpolations of the DSP and $V_{30}$ attributes using other techniques available in ArcMap 9.1.
5.0 Output Surfaces and Prediction Error Statistics

5.1 Prediction accuracy

Measures of prediction accuracy calculated by Geostatistical Analyst are provided during cross-validation and include the mean, root-mean-square, average standard error, mean standardized, and the root-mean-square standardized error. The mean and root-mean-square are available for both geostatistical (kriging) and deterministic (e.g., splines) interpolation methods. The average standard error, mean standardized, and root-mean-square standardized statistics, which provide measures of uncertainty in the predictions (i.e., how good are the predictions) are available only for the geostatistical methods, however.

Parameters may be selected and changed to achieve optimal prediction error statistics. Once the process has been completed, the prediction errors associated with each method can be compared, as well as graphs of the predicted, error, standardized error, and QQ plots from each method (Figure 40).

5.2 Mean Dynamic Site Period (DSP)

5.2.1 Prediction Map

Universal cokriging, using depth-to-bedrock values as a correlating variable, was used to produce the DSP prediction map. The resulting prediction error values suggest this method produced the most accurate results. If the predicted values are unbiased (centered on the true values), the mean should be near zero. For this interpolation, the calculated mean was –0.005278. The root-mean-square error (RMS) measures how close the predicted values are to the measured values, and the RMS should be as small as possible (the closer to zero the better). The RMS was 0.2298.

The remaining measurements detail the validity of the results, describing the uncertainty in the predictions. Average standard error (ASE) is a measure of the variability of the prediction and should be close to the RMS value. Here, the ASE was 0.1989, a difference of 0.0309 from the RMS. If the ASE is greater than the RMS
Figure 40. The cross validations from multiple output surfaces can be compared side-by-side.
the variability in prediction is overestimated, and if the ASE is less than the RMS, the prediction variability is underestimated. The mean prediction error depends on the scale of the data, so the mean standardized error is calculated by dividing the prediction errors by the prediction standard errors. The mean standardized error should be as close to zero as possible. In this case, the calculated value was –0.02963. Root-mean-square standardized error is another measure of variability and is calculated by dividing each prediction error by its estimated prediction standard error. These values should be similar, resulting in RMS standardized values close to 1 if the prediction standard errors are valid. If the value is greater than 1, the prediction variability is underestimated. Values less than 1 indicate overestimation of variability. The interpolation of DSP using universal cokriging resulted in an RMS standardized value of 1.07.

Inspection of the DSP output surface allows conclusions to be drawn concerning the geological and geophysical nature of the Jackson Purchase Region. First, trends in the distribution of DSP values are clearly visible. Areas with mean dynamic site periods ranging from 1.0 to 3.0 extend from north to south in parts of McCracken County (predominantly in the central and western sections of the county), Ballard County (predominantly in the southeastern half of the county), Carlisle County (in most areas except in the east), Hickman County (covering the vast majority of the county), and Fulton County (in the northwestern and northeastern sections of the visible study area). Parts of west-central, east-central, and northeastern Graves County show DSP values above 1.0, as well as the northern half of Marshall County and the eastern half of Calloway County.

Figure 41 shows the DSP output surface with bedrock depth distribution. The positive correlation between the two variables is observed graphically where deeper bedrock depths align with higher dynamic site periods.

Caution should be taken when examining areas of the map with few sample points (e.g., the northwestern, south-central, and eastern edges of the map, as well as the north-central and south-central parts of Graves and McCracken Counties, respectively). Two additional areas, central Hickman County and west-central Graves County, also contain few sample points. In these areas, the scarcity of sample points results in less-reliable predictions, sometimes referred to as “edge effects.”
Figure 41. Distribution of bedrock depths over DSP output surface. Higher dynamic site periods correlate with deeper sediments.
5.2.2 Prediction Standard Error Map

The prediction standard error map shows the distribution of prediction standard errors calculated for every point on the output surface (Figure 42). Higher error values are represented by darker colors, and lower error values by lighter colors. As expected, error values are highest in areas with the fewest sample points, such as in north-central Graves County. In this area, errors with values as high as about 0.3 are recorded, whereas in the vicinity of Paducah in McCracken County, where many more sample points are located, providing better control on the distribution of DSP values, error values of about 0.09 are common.

Using the prediction standard error map, areas can be identified where additional field measurements may be necessary. Conversely, areas of high sampling density and, therefore high confidence in the predicted values, can be identified. For example, if knowledge of the mean dynamic site period for locations in north-central Graves County is needed, additional field investigation to determine DSP should be conducted rather than relying completely on the values predicted by Geostatistical Analyst.
Figure 42. The prediction standard error map derived from the DSP prediction map shows graphically the calculated uncertainty in the predictions. Light colors represent areas of low uncertainty, and dark colors represent high uncertainty as a result of lack of sample locations.
5.3 Weighted Shear-Wave Velocity of the Upper 30 m of Soil (V30)

The interpolation techniques used for the DSP output surfaces, other than cokriging, were also used to interpolate V30 values over the same study area using data collected at the same sample locations (Figure 43). Resulting accuracy statistics indicate that prediction of V30 values over the study area was unsuccessful (Figure 44). The prediction error statistics were:

Mean: −0.1273
RMS: 79.7
Average standard error: 73.13
Mean standardized: −0.003095
RMS standardized: 1.078

The RMS error shows that there was a very large discrepancy in the predicted values versus the actual measured values. For this reason, the output surface of interpolated V30 values is not considered a true representation of the geophysical reality of the Jackson Purchase Region and should not be used to infer relationships of V30 values from one location to another within the study area. Figure 45 is a prediction standard error map derived from the V30 prediction map showing areas of high uncertainty in areas with few sample locations.

The difficulty with interpolation of V30 arises as a result of the lateral variation in stratigraphy in the Jackson Purchase. Thicknesses of individual soil layers and their s-wave velocities are used for V30 calculation. The thickness of a layer determines how much weight is given to its velocity, as shown in the equation $V_{30} = \frac{30}{\sum_{i=1}^{n}(h_i/v_i)}$ (BSSC, 1997). High variation in stratigraphy, thicknesses of individual soil layers, and layer velocities over short distances within the study area cause high interpolation prediction errors. In contrast, DSP values are dependent only on the total thickness of the soil/sediment overburden and the weighted-average velocity of all layers, parameters that are much more consistent over the entire study area than thicknesses and velocities of individual layers. This accounts for the discrepancy in prediction error statistics of DSP and V30 values.
Figure 43. The output surface showing distribution of $V_{30}$ values.
Figure 44. Cross-validation summary statistics of prediction errors for $V_{30}$ output surface.
Figure 45. Prediction standard error map derived from $V_{30}$ output surface.
5.4 Deterministic Methods

In addition to the kriging methods, deterministic techniques were considered. Although these methods, including inverse distance weighted (IDW), global and local polynomial, and radial basis functions, including splines, produced surfaces with RMS values approximately 0.45, no means are available for assessment of uncertainty in the predictions. These methods are ideal for fast interpolation and can provide output surfaces for use in general examination of trends in a study area when no detailed uncertainty statistics are necessary.

The surface shown in Figure 46 was produced using a completely regularized spline. The RMS error was 0.4412 with mean prediction error of –0.007481. Although the RMS error was smaller using the universal cokriging method, the spline method still produced a relatively accurate result. Though there are no associated measures of uncertainty, and prediction standard error maps cannot be created from deterministic method output surfaces, the spline output surface can be compared with the kriging surface to show the similarities between them. Cokriging clearly produces a more detailed surface, but the spline surface shows agreement with the major trends in DSP distribution across the study area.
Figure 46. The completely regularized spline surface shows regional DSP trends.
6.0 Conclusion and Considerations

Over the last 20 years, researchers at the University of Kentucky have collected seismic reflection/refraction data for characterization of the seismic velocity models of the soil/sediment overburden throughout the central United States. These data and associated information have been difficult to manage because of the lack of a centralized repository to assist storage, retrieval, and analysis. The goal of this project was to use the ESRI ArcGIS software tools to make these data accessible and manageable and to use some of the tools available with this software for spatial and geostatistical analysis in order to provide a regional assessment of dynamic soil properties used in seismic hazard analysis.

To accomplish this goal, the data were gathered from various journals, publications, theses, and dissertations and digitized and stored in a personal geodatabase using ArcCatalog 9.1. The data were then projected on a digital map in ArcMap, and the data from the Jackson Purchase Region of western Kentucky were used to produce derivative maps in the Geostatistical Analyst extension of ArcMap. Exploratory spatial data analysis was used to examine characteristics of the dataset, particularly the mean dynamic site period and V\textsubscript{30} attributes associated with each sample site. Based on this information, the universal cokriging method was selected as the optimal technique for interpolation of the DSP data across the study area. Other methods, including deterministic methods and other geostatistical techniques, were considered, but analysis revealed that the kriging methods in general, and the universal cokriging method in particular, produced the most accurate results. Cokriging uses two datasets presumed to be correlated to each other for mathematical and statistical modeling of the output surface. The directly proportional relationship between the dynamic site period and depth-to-bedrock datasets was the basis for the decision to use the cokriging interpolation method.

Interpolation of V\textsubscript{30} was unsuccessful as a result of the lateral variation in soil layer thicknesses and velocities. Further research is recommended to determine if interpolation of V\textsubscript{30} is possible over smaller scales.

When using Geostatistical Analyst interpolation capabilities to produce output surfaces, it is advisable to remember that the scale of the surface under investigation may have an effect on the way the results should be interpreted. This, of course, depends on the purpose for which the output surfaces are being created. Although prediction error statistics are calculated by Geostatistical Analyst to quantify the prediction accuracy of the output surfaces, the researcher
must judge, according to the stated aims of the project, the validity of the results. Errors calculated for a surface spanning the Jackson Purchase Region may translate into differences on the order of tens of meters, whereas errors calculated for a study area such as the city of Paducah may represent only a few meters. The implications may be significant, depending on the nature of the project and will compel the researcher to use caution when interpreting the results of output surfaces.

6.1 Future Work

6.1.1 Database Design

The structure used to develop the database is relatively simple. Each of the feature classes are nearly identical and are divided by source and geographic location. Some feature classes contain more attributes than others, depending on the nature of the original research. For this project, the goal was to digitize the data and store it in a common location. The data were used to produce interpolated derivative maps useful in future research related to seismic hazard assessment. The structure of the database allows the addition of new data and data types. As the database grows and the intended use of the data evolves, attention to the structure and design of the database is recommended. It may be necessary to reconfigure the database in order to accommodate new data and data types to maximize the potential of the database. Hernandez (1997) is an excellent resource for database design considerations. The ArcGIS database platform is ideal for storage of multiple interrelated data types. Raster images, such as stacked seismic profiles and photographs from study areas, core data, soil classifications and descriptions, and other geotechnical data should be included in the database.

6.1.2 Field Work

To improve the accuracy and reliability of output surfaces using interpolation techniques available in Geostatistical Analyst, further field sampling of seismic velocities and other geophysical attributes is recommended. More sample locations, particularly in areas where few already exist, would likely improve interpolation accuracy. Several references are available that discuss sampling regimes for optimal interpolation performance, including Laslett (1994), Carver (1997), O’Sullivan and Unwin (2003), Arlinghaus (1996), and Schabenberger and Gotway (2005).
Appendix A

A comprehensive list of data tables included in the database, showing all fields and data.
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Wang–Louisville, KY, sites.
Appendix B

The following maps show the results from interpolation of both the DSP and $V_{30}$ attributes using each of the applicable techniques available in Geostatistical Analyst 9.1. The prediction error statistics for each map are included. It is evident that interpolation of DSP values was successful; each of the derivative maps have RMS values less than 1. The interpolation of the $V_{30}$ attribute, however, was unsuccessful for all techniques. RMS values for $V_{30}$ derivative maps ranged from 79 to over 100, a few orders of magnitude higher than those achieved by interpolation of the DSP attribute.
DSP Interpolated Maps
Simple Kriging (DSP)
Mean: -0.008543
Root-Mean-Square: 0.4149
Average Standard Error: 0.2829
Mean Standardized: -0.02485
Root-Mean-Square Standardized: 1.369
Simple Cokriging (DSP)

Mean: 0.0007828
Root-Mean-Square: 0.3787
Average Standard Error: 0.2761
Mean Standardized: 0.004697
Root-Mean-Square Standardized: 1.221
Inverse Distance Weighted (DSP)
Mean: -0.01489
Root-Mean-Square: 0.4577
Global Polynomial (DSP)
Mean: 0.001094
Root-Mean-Square: 0.5298
Local Polynomial (DSP)
Mean: 0.004424
Root-Mean-Square: 0.5117
Spline with Tension (DSP)
Mean: 0.9071
Root-Mean-Square: 78.38
Multiquadric Spline (DSP)
Mean: -0.007199
Root-Mean-Square: 0.4681
Inverse Multiquadric Spline (DSP)
Mean: -0.01416
Root-Mean-Square: 0.463
Thin Plate Spline (DSP)
Mean: -0.007255
Root-Mean-Square: 0.5315
Ordinary Kriging (DSP)

Mean: 0.01556
Root-Mean-Square: 0.4341
Average Standard Error: 0.3018
Mean Standardized: 0.04384
Root-Mean-Square Standardized: 1.304
Ordinary Cokriging (DSP)

Mean: -0.004087
Root-Mean-Square: 0.3601
Average Standard Error: 0.2831
Mean Standardized: -0.01107
Root-Mean-Square Standardized: 1.147
Simple Cokriging (DSP)

Mean: 0.0007828
Root-Mean-Square: 0.3787
Average Standard Error: 0.2761
Mean Standardized: 0.004697
Root-Mean-Square Standardized: 1.221
Universal Kriging (DSP)

Mean: -0.002872
Root-Mean-Square: 0.4519
Average Standard Error: 0.2254
Mean Standardized: -0.00163
Root-Mean-Square Standardized: 1.795
$V_{39}$ Interpolated Maps
Inverse Distance Weighted ($V_{30}$)

Mean: 1.173

Root-Mean-Square: 79.59
Global Polynomial (V30)
Mean: -0.1828
Root-Mean-Square: 80.77
Global Polynomial using higher-order polynomial ($V_{30}$)

Mean: -1.194
Root-Mean-Square: 87.54
Local Polynomial (V30)
Mean: -7.123
Root-Mean-Square: 80.09
Completely Regularized Spline (V₃₀)
Mean: 1.076
Root-Mean-Square: 78.78
Spline with Tension ($V_{30}$)
Mean: 0.9071
Root-Mean-Square: 78.38
Multiquadric Spline ($V_{36}$)
Mean: 0.4201
Root-Mean-Square: 84.18
Inverse Multiquadric Spline (V₃₀)
Mean: 1.932
Root-Mean-Square: 77.85
Thin Plate Spline ($V_{30}$)
Mean: 1.153
Root-Mean-Square: 98.79
Ordinary Kriging ($V_{30}$)

Mean: 0.6137
Root-Mean-Square: 79.55
Average Standard Error: 68.96
Mean Standardized: 0.008499
Root-Mean-Square Standardized: 1.133
Simple Kriging ($V_{30}$)

Mean: 1.155
Root-Mean-Square: 80.36
Average Standard Error: 64.16
Mean Standardized: 0.01027
Root-Mean-Square Standardized: 1.21
Universal Kriging ($V_{30}$)

Mean: 0.09248
Root-Mean-Square: 79.32
Average Standard Error: 68.29
Mean Standardized: 0.001597
Root-Mean-Square Standardized: 1.143
References


VITA

-Born February 10, 1977, in Santa Maria, California.

Education

-University of Kentucky, Lexington, Kentucky, 2000 – 2004
  Bachelor of Science – Geology

Experience

-Kentucky Army National Guard, 1999 – 2004
-United States Army, 1996 – 1999

Honors and Activities

-Presented thesis research poster at the Seismological Society of America sectional meeting, 2005
-Presented research findings at the Seismological Society of America sectional meeting, 2005
-Recipient of Graduate School Pirtle academic scholarship, 2005 and 2006
-Attended field camp as a student, Montana; 6-week structural geology mapping course, 2004

David M. Vance