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Seismic Velocity Database for the New Madrid Seismic Zone and Its Vicinity

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Technical Level

General	Intermediate	Technical

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Seismic Velocity Database for the New Madrid Seismic Zone and Its Vicinity

Qian Li, Edward W. Woolery, Matthew M. Crawford, and David M. Vance

Abstract

Over the last 20 years, researchers at the University of Kentucky have collected seismic-reflection and refraction data to characterize seismic velocity models of the soil-sediment overburden throughout the central United States. The data are in different forms, such as published reports, theses, and journal articles, and in digital form. In order to construct a unified database for easier management, access, and use, Microsoft Access was used to design the data structure and field properties. The database consists of four tables with unified field names, data type, and units. An ArcGIS geodatabase with the same data structure as the Access database was then created for visualization and querying capability. The compiled seismic velocity data used the same data types and units, and were stored in both databases. The databases are flexible, so that new data and data types can be added and joined with existing databases at the Kentucky Geological Survey.

Introduction

Seismic velocity data are primarily used to characterize and model the soil-sediment overburden in order to determine the ground-motion site effects during an earthquake. The weighted-average shear-wave velocity of the upper 30 m (Vs_{30}) of soil-bedrock, in particular, has been used to account for ground-motion site effects in the National Earthquake Hazards Reduction Program provisions (Building Seismic Safety Council, 1998, 2009). Nonlithified sediments, including alluvial deposits, can alter ground-motion characteristics such as amplitude, frequency content, and duration (Kramer, 1996). A classic example of these site effects was in September 1985, when parts of Mexico City were severely damaged during the Michoacan earthquake, whose epicenter was nearly 300 km away. The greatest damage resulted from ground-motion amplification through 10 to 80 m of lake-bed sediment (Singh and others, 1988). Woolery and others (2008) showed that the significant damage ($3

million) in Maysville, Ky., was caused by amplified ground motion of the near-surface soft soils during the 1980 Sharpsburg earthquake. Much of the New Madrid Zone is underlain by thick, unlithified deposits of sand, gravel, and clay (Fig. 1), which can cause local ground-motion site effects. The New Madrid Seismic Zone and nearby Wabash Valley Seismic Zone are complex systems of faults mostly beneath the surface and are outlined by epicenters of earthquakes (Fig. 2). The New Madrid Seismic Zone is one of the most seismically active areas east of the Rocky Mountains and home to an average of 200 earthquakes a year with magnitude greater than M 1.5 (Williams and others, 2011).

During the last two decades, researchers at the University of Kentucky have collected much seismic velocity data, particularly from the vicinity of the New Madrid Seismic Zone, including western Kentucky, southeastern Missouri, northeastern Arkansas, and northwestern Tennessee. Many data have also been acquired from the Wabash Valley Seismic Zone, located in southern Indiana and Il-
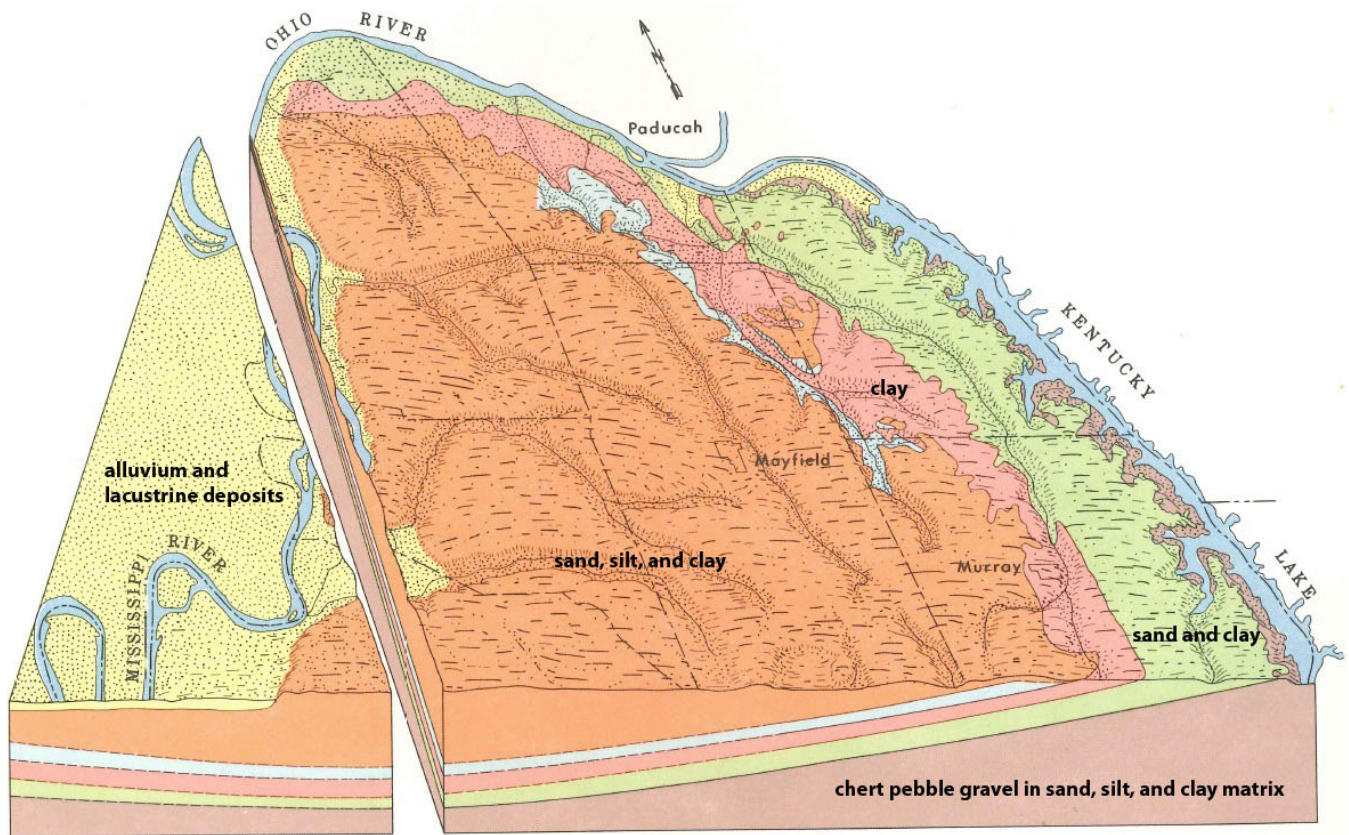
Figure 1. General stratigraphy of Cretaceous to Holocene sediments and semiconsolidated sediments in the northern part of the Mississippi Embayment, part of which contains the New Madrid Seismic Zone. Modified from Olive (1972).

linois. Additional velocity data associated with seismic-hazard microzonation investigations have been collected from Paducah, Henderson, Louisville, and Maysville, Ky.

An ArcGIS 9.1 personal geodatabase containing many of these data was compiled by David M. Vance in 2006. We converted Vance's (2006) database to a unified database in order to systematically collect, organize, and make the data accessible. The data in Vance's (2006) database were collected at 519 sites by researchers at the University of Kentucky: Harris (1992), Al-Yazdi (1994), Higgins (1997), Street (1997), Street and others (1997, 2005), Wood (2000), Lin (2003), and Wang and others (2004).

The Data
Acquisition and Processing
of Seismic Velocity Data

Two sets of seismic data were generally acquired by the UK researchers: (1) P-wave reflection soundings to the top of the Paleozoic bedrock and (2) reversed SH-wave refraction and reflection profiles (used to determine the S-wave velocities of the unlithified sediments to depths as great as 200 m).

The energy sources used for P-wave data acquisition were a seismic hammer and vacuum-assisted weight drop. The receivers were inline spreads of 24 or 48, 40-Hz vertical-component geophones spaced at intervals ranging between 2 and 10 m. The seismic hammer was used at most sites, particularly where the depth to bedrock was less than 100 m. At some of the sites, the depth to the water table was also determined. Early investigations often used the weight drop for sites where the depth to bedrock exceeded 100 m, but in the early 2000's this energy source became obsolete. In nearly all cases, the energy source was used at the 0-m offset position and stepped out to offsets of one to four times the length of the geophone spread, depending upon the length of the geophone spread, the quality of the recorded signal, and the depth
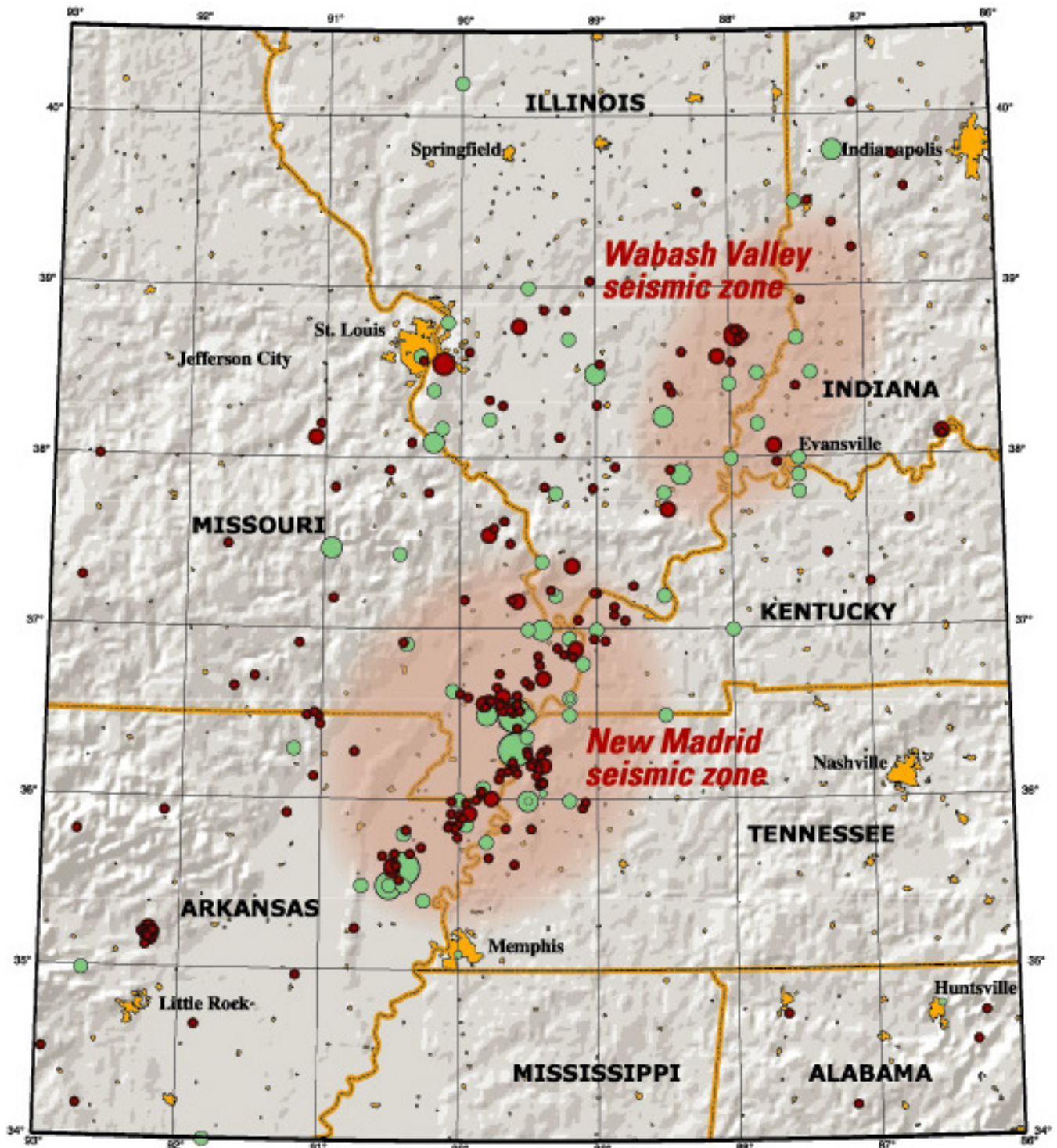
Figure 2. Locations of selected earthquake epicenters larger than M 2.5 in the New Madrid and Wabash Valley Seismic Zones (U.S. Geological Survey, 2002).

to bedrock. This technique allowed both the refraction and reflection signals to be used (Fig. 3).

SH-wave data were acquired using a seismic hammer striking a steel I-beam in the manner described in Street and others (1995). Inline spreads of 24 or 48, 30-Hz horizontally polarized geophones were spaced at intervals ranging between 2 and 6.1 m. The seismic hammer was used at the 0-m off-
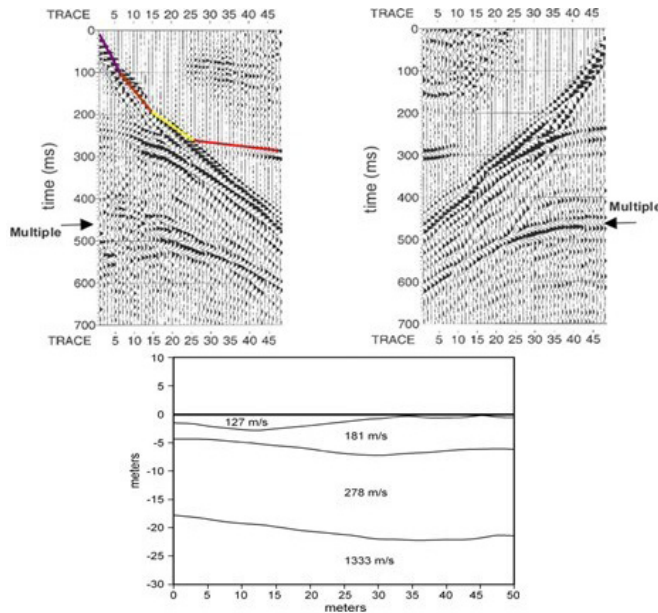
Figure 3. (a) Example of a processed, reversed SH-wave seismic-refraction/reflection sounding. Data were collected at a sampling rate of 0.25 ms, from an inline spread of 48 geophones spaced at 2 m. (b) S-wave velocity and depth model interpreted for the site from the first-arrival time.

set positions at both ends of the geophone spreads and often at various stations within the array, so as to achieve high-quality reciprocity. Similar to the P-wave acquisition, the source was often stepped out to offsets of one to four times the length of the geophone array. To ensure the accurate identification of SH-mode events, impacts were recorded on each side of the energy source; striking each side of the source and reversing the acquisition polarity of the engineering seismograph results in inadvertent P- and SV-mode energy stacking in a destructive manner, whereas SH-mode energy stacks constructively.

The P- and SH-wave field files were processed by computer using the commercial software package VISTA 7.0 (Seismic Image Software Ltd.). Typical processing consisted of converting the raw files into SEG-Y format files, bandpass filtering, applying an automatic gain control, and using a frequency-wave number filter to remove residual ground roll. Timing corrections due to changes in elevation between the shotpoint and geophones were included in the processing when necessary, but because the seismic profiles were often acquired at sites with little or no relief, this was infrequently required. Various bandpass filters, automatic gain

control windows, and frequency-wave number filters were applied to the data because of depth variations and the field conditions encountered (i.e., highway traffic, irrigation pumps, soil types, etc.).

The reflection-derived velocities used the two-way intercept times and stacking velocities from interpreted P- and SH-waves, which were estimated using VISTA 7.0's interactive hyperbolic curve-fitting computer algorithm for the X2-T2 analysis. The interval velocities and subsequent layer thicknesses were calculated using Dix's (1955) equation.

The first-break arrival times for the refracted SH-waves, as interactively picked with the seismic-refraction software package SIPT2 v. 4.1 (Rimrock Geophysics Inc.), were used to derive S-wave velocity-depth models. SIPT2 uses the delay-time method to obtain a first approximation of the velocity-depth model by comparing the observed first-break picks to those computed using ray tracing. The model is then iteratively adjusted to decrease the travel-time differences between the first-break picks and model-calculated arrival times.

Downhole S-wave measurements were collected at a few sites. These surveys were conducted by placing an S-wave energy source on the ground surface approximately 2 m from the borehole well-head and using a triaxial geophone array placed at various elevations in the borehole. A downhole survey measures the travel time of the seismic wave from the energy source to various elevations of the geophone. More important, the downhole survey forces the travel path of the seismic wave to traverse all strata between the energy source and receiver; therefore, it detects low-velocity inversion layers. The energy source used to acquire the data in Vance's (2006) database was a section of steel H-pile struck horizontally by a 1-kg hammer. The hold-down weight on the H-pile was approximately 70 to 80 kg. The flange of the source opposite the side receiving the hammer blow was embedded into slots cut into the surface to improve the energy coupling. The downhole receiver used in all surveys was a Geostuff model BHG-2c, 14-Hz, three-component geophone. A geophone-to-borehole coupling was developed via a motor-driven piston that expanded and contracted a wall-lock spring. At each downhole collection point, shear-wave arrival times were acquired from orthogonal directions (i.e., arbitrary longitudinal and transverse

directions) (Fig. 4). This decreased the potential effects associated with repeatability (timing offsets) and preferred axial orientations (anisotropy). The earliest-arriving shear wave was assumed to represent the average shear-wave velocity to a given depth. Each data-collection point was vertically stacked three to 10 times in order to improve the signal-to-noise ratio.

An initial test of uncorrected polarization was usually performed to ensure that shear waves were properly identified (Fig. 5). Subsequently, individual traces were corrected for polarity, bandpass filtered, gain controlled, and spliced into an overall downhole composite. The first-break travel-time picks were interactively selected using VISTA 7.0, and the shear-wave velocity profile was subsequently calculated using generic spreadsheet algorithms.

In general, the data were recorded on Geometrics engineering seismographs, but of various models. The majority of the data were acquired with a 24-bit, 48-channel instantaneous floating-
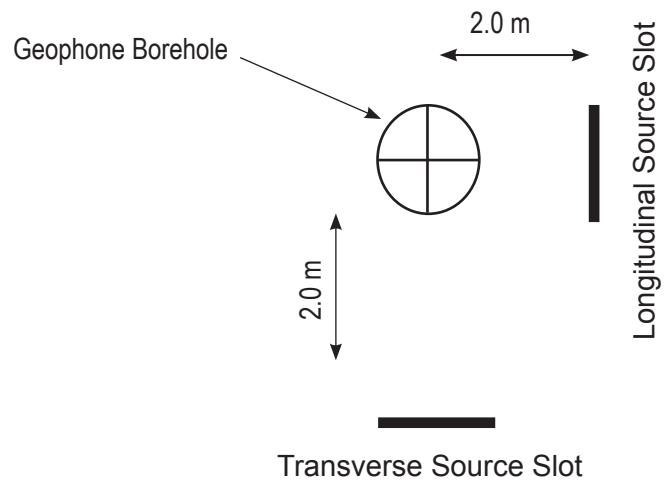
Figure 4. Plan view of the downhole seismic-survey acquisition geometry.

point model with a sampling interval between 0.20 and 0.50 ms.

Data Accessibility

The usefulness of the seismic-velocity data soundings acquired by the UK researchers was limited because of the inaccessibility of the data. Often, the data were not 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, examining data to identify trends and derive useful information was often difficult because spatial representation and rapid manipulation of the data set was difficult. Our new database allows queries and spatial representation in map form. Specifically, it provides a view of the sample-site distribution and allows statistical analysis that would be too cumbersome to perform by hand.

Procedure

To begin database compilation, we (1) retrieved seismic-velocity data collected by University of Kentucky researchers from
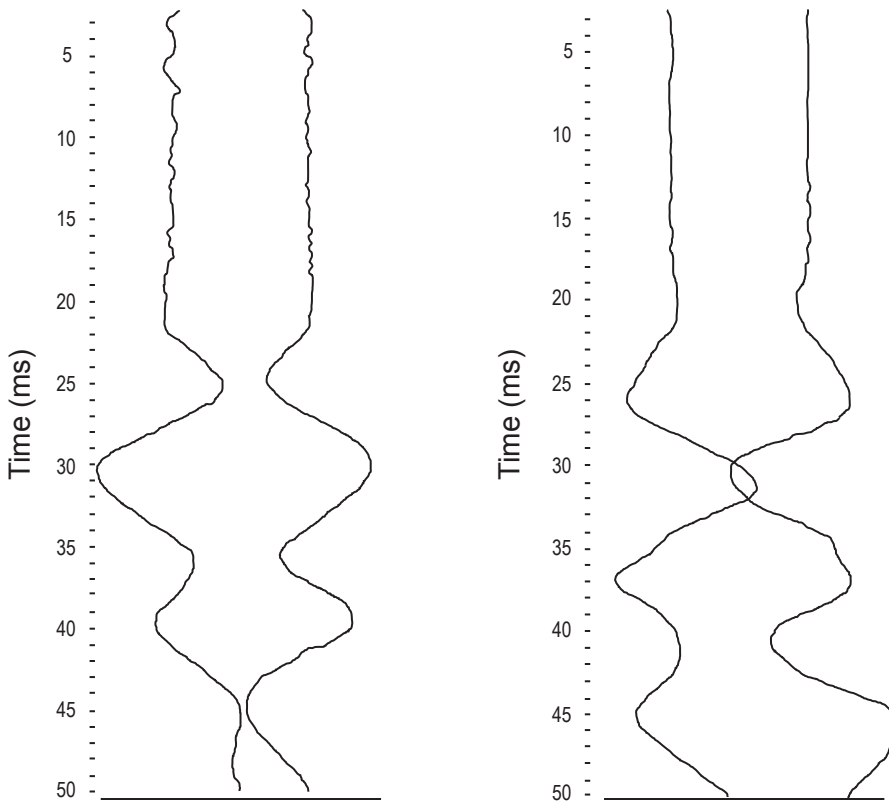
Figure 5. Uncorrected polarity tests were performed on the longitudinal (left) and transverse (right) elements of the downhole geophone in order to ensure correct identification of the shear wave.

various media, (2) digitized the data and organized them by project, and (3) interpolated pertinent dynamic properties for seismic-hazard assessments, such as Vs_{30} and dynamic site period.

Vance (2006) constructed an ArcGIS geodatabase using tables from Microsoft Excel. Each Excel table was converted to an ArcGIS feature class to ensure a common spatial reference. The feature classes were organized according to researcher and site location.

Vance's (2006) geodatabase has a horizontal structure; every feature class corresponds to one project and contains seismic data from along multiple profiles in an area. Each record is a point that represents a seismic profile site from which the data were collected. The site-coupled information included latitude-longitude coordinates, depth to bedrock, weighted-average shear-wave velocity of the upper 30 m of the soil-bedrock layer, and site name, and was stored in one record. Because of the database's horizontal structure, the vertical soil-layer information could only be stored in one record, making it difficult to view and query vertical velocity data for soil horizons.

Table 1 shows that field data types, field names, and attribute values were inconsistent in Vance's (2006) database. For example, the coordinate information contained field names such as "LAT," "LONG," "Y__LAT_," "X__LONG_," and the data types were both double and long integer. Some feature classes had more attributes than others, depending on the nature of the original research. For example, some projects had four or five soil layers with corresponding thicknesses and velocities, but for other projects, only single soil layers were attributed.

Thus, Vance's (2006) database containing variable data from multiple collectors needed to be transformed to a design that is compatible with other KGS databases for consistent data access, advanced querying, and spatial analysis. An improved data structure that allows for easy population of new and older data ensures consistency and a framework that allows the data to be analyzed in a spatial context.

New Database Compilation and Design

A new database was constructed using the seismic data compiled by Vance (2006). The new database unifies the structure and contents, reduces redundant data, and provides better flexibility for future addition of new data. The new database was structured as related tables corresponding to a seismic site. Field names, data types, and attribute values were unified. The horizontal data structure was converted into a vertical data structure. A data table that allows for attribution of velocity and thickness in vertical from-to intervals was designed. All layers of the data were related and duplicate records were eliminated.

Microsoft Access

Microsoft Access is a relational database management system that allows users to store, organize, and manage tabular data. Its main advantage for our purposes is the revisable field design and the relationships between different tables. The field properties, including the field name, the position of the fields, and the data type, can be amended, deleted, or inserted. An Access database can also easily be transformed into an ArcGIS geodatabase for spatial analysis.

Database Structure Design

The new database structure contains four tables. The design structure is shown in Figure 6. The Seismic Project table contains the source data, and

Table 1. Selected field names and data types in the shear-wave velocities database compiled by David M. Vance (2006). The headings are the names of feature classes in Vance's database, organized by collectors and site names. Every feature class has a different field name and data type; empty cells mean that the correlated data did not appear in this feature class.

Harris_Paducah		Higgins_Henderson		Street_Arkansas		Ting_Li_Maysville		Wood_Memphis	
X_LONG_	long integer	LAT	double	LAT	double	LAT	double	LAT	double
Y_LAT	long integer	LONG_	double	LONG_	double	LONG_	double	LONG_	double
ELEV_FT_	long integer			ELE__FT_	long integer			ELEVATION_	double
DEPTH_FT	long integer	BED_VEL_M	double			BEDROCK_VE	double		
Vs_{30}	double	Vs_{30}	double	Vs_{30}	short integer	Vs_{30}	float	Vs_{30}	double

includes the name of the researcher or the provider of the data and the location from which they were obtained. Every record represents one project and contains data collected from several sites. Each record in this table can be related to many records in the Seismic Site table.

The Seismic Site table contains all the necessary identifiers, spatial locations, and site properties concerned with the site, including ID fields, site name, site subtype, coordinates, date, elevation, depth to bedrock, Vs_{30}, and density.

The Seismic Data table contains vertical soil-layer structure, layer order, depth, thickness, and, most important, the velocity of every soil layer.

The Images table contains associated images or other documents, and can be correlated to information in the Seismic Site table. The attached documents or images are stored in a centralized folder and named so that they can be associated with a seismic-site ID.

Field Properties

Field data types for the new database were chosen to maintain consistent attribute values. Ta-

Seismic Site

SeismicSiteID (new number, unique)
ProjectID
OldSiteID
Lat
Long
SiteSubType
SiteName
Date
Elevation__m
Depth To
Bedrock__m
Vs_{30}
Density

Seismic Project

ProjectID
ProjectName
SourceName

One-to-many [ProjectID]

One-to-many [SeismicSiteID]

[SeismicSiteID]

Seismic Data Table (many records for one site)

LayerID (automatic by Access)
SeismicSiteID
LayerOrder (lower # is shallower)
From__m
To__m
Thickness__m
Velocity__m_s

Images Tables

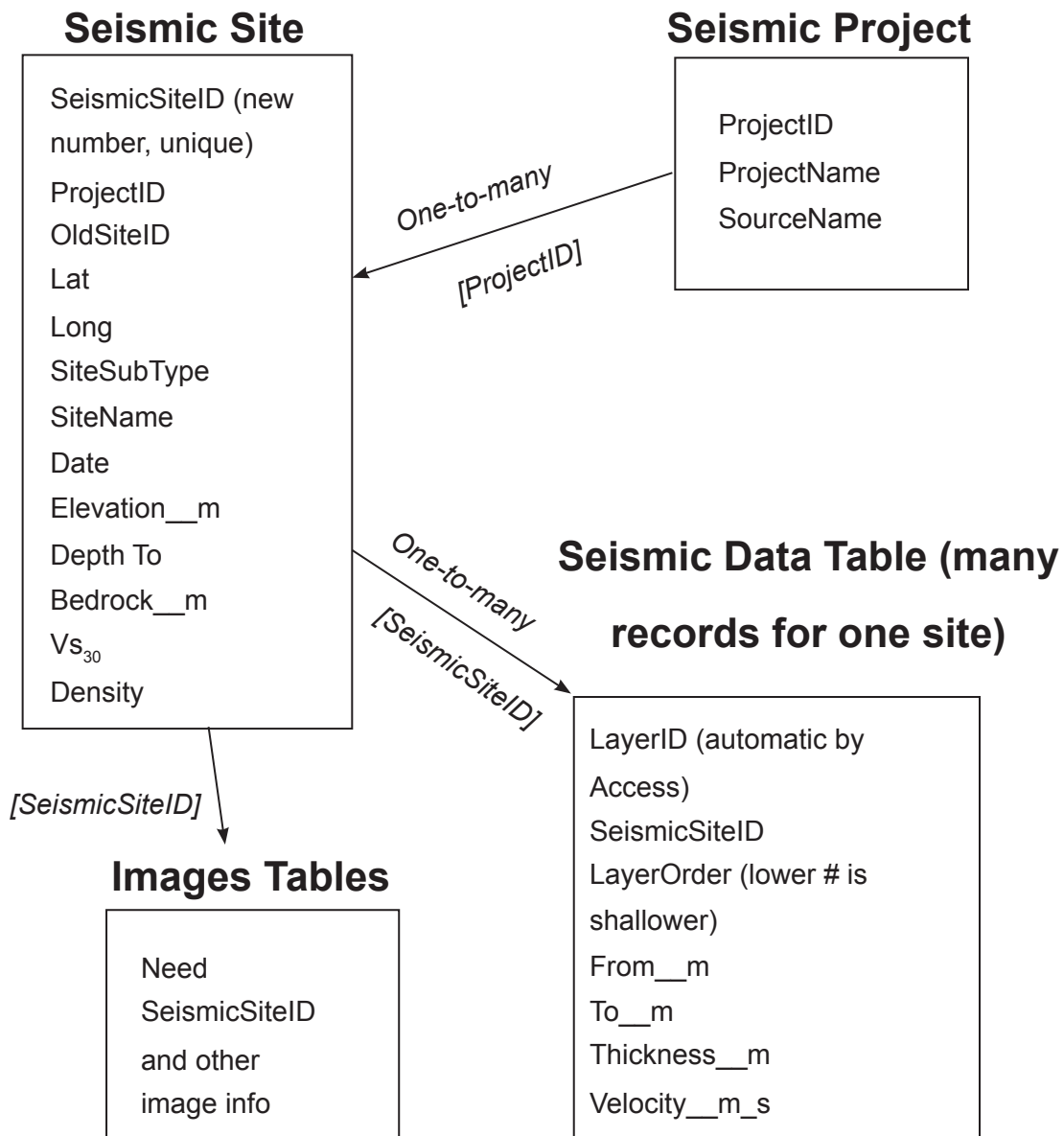Need SeismicSiteID and other image info

Figure 6. Structure of the four-table database and contents.

bles 2 through 5 show the field properties of the tables.

In order to have a unified data type, all number data were designated as double. For example, the distance units in Vance's (2006) database were both feet and meters, and the velocity units were both feet per second and meters per second. The inconsistent data types made comparing data sets from different projects difficult. The new database uses only meters and meters per second.

The project ID, seismic site ID, and old site ID are important fields in the new database. Every project in the Seismic Project table has a unique ID number that can index this project and connect its records to other tables. The seismic site ID in the Seismic Site table uniquely identifies every seismic site for all projects.

Relationships Design

The power of a relational database in Access is that the data are consistent from table to table. With the design of the ID fields, the data from different tables can be connected using primary key fields (Fig. 7). Every seismic project record can match many site records in the Seismic Site table, but a site record can match only one project record in the Seismic Project table. According to the same principle, a site record can also match several soil-layer and velocity data, and many attached images or documents. These types of relationships are one-to-many relationships.

In this new database, the project ID is the field that connects the Seismic Project table and the Seismic Site table. The seismic site ID is the field that connects the Seismic Site table to both the Images table and Seismic Data table.

Results

Compilation of Vance's (2006) seismic data resulted in a Seismic Project table containing nine records representing projects from western Kentucky, southeastern Missouri, northeastern Arkansas, northwestern Tennessee, and the Wabash Valley Seismic Zone of southern Indiana and Illinois. Additional microzonation data have been collected from Paducah, Henderson, Louisville, and Maysville, Ky. Data for every project were collected from several sources: Woolery (2009), Woolery and others (2009), and Chiu and others (2012). The Seismic Site table contains data from 665 sites. Some of the sites have corresponding layer information, such as thickness of overlying soil layers and velocity of each layer. The Seismic Data table

Table 2. Field properties of the Seismic Project table.

Field Name	Data Type	Field Size	Required
Project ID	number	double	yes
Project Name	text	50	yes
Source Name	text	50	no

Table 3. Field properties of the Seismic Site table.

Field Name	Data Type	Field Size	Required
Seismic Site ID	number	double	yes
Project ID	number	double	yes
Old Site ID	text	50	no
Lat	number	double	no
Long	number	double	no
Site Subtype	text	50	no
Site Name	text	30	no
Date	date/time	–	no
Elevation_m	number	double	no
Depth to Bedrock_m	number	double	no
Vs30_m_s	number	double	no
Density	number	double	no
Comments	text	255	no
Array Name	text	50	no

Table 4. Field properties of the Seismic Data table (shear-wave velocities).

Field Name	Data Type	Field Size	Required
Seismic Site ID	number	double	yes
LayerOrder	number	double	yes
From_m	number	double	no
To_m	number	double	no
Thickness_m	number	double	no
Velocity_m_s	number	double	no
MapUnit	text	50	no

Table 5. Field properties of the Images table.

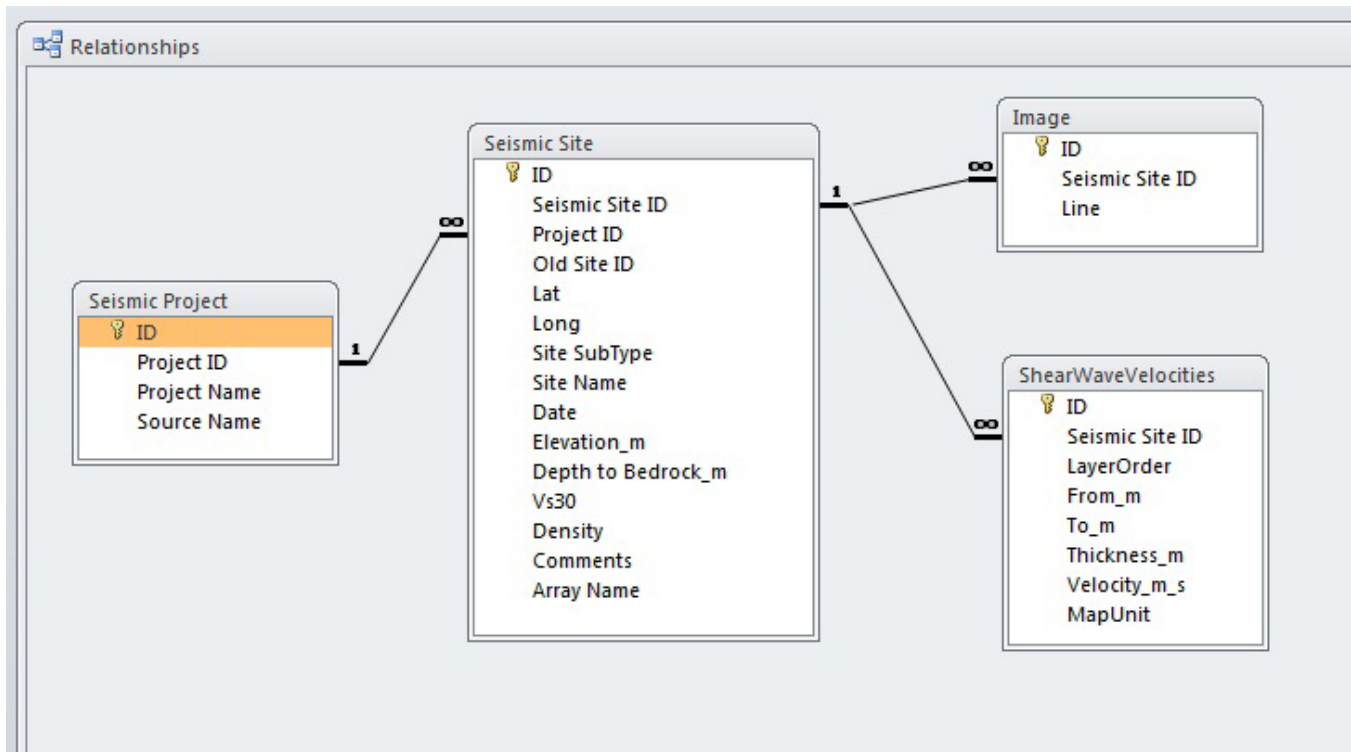| Field Name	Data Type	Field Size	Required
Seismic Site ID	number	double	yes
Document	hyperlink	–	yes

Figure 7. Relationships that connect the different tables with each other in a Microsoft Access database. The field ID's are the unique numbers for every record in each table, and the project ID and seismic site ID are the key fields that connect the tables.

contains 713 records of layer information (Fig. 8). Corresponding documents or images can be added to the database in the Images table and related to the Seismic Site table with the seismic site ID.

Use of ArcGIS
Advantages of ArcGIS Geodatabase

The new database produced in Access is simple, concise, and flexible, but it also has disadvantages. A data storage size limit and inability to spatially visualize the data prompted creation of a new ArcGIS geodatabase. The newly compiled seismic data contain geographic information, and spatial queries and visualization are also goals of a new unified database. Therefore, using the Access database structure, an ArcGIS geodatabase was populated to provide a geographic information system for spatial visualization.

GIS Data Structure and Relationships

The structure from the Access database was transferred to the new ArcGIS geodatabase. This includes the Seismic Project table, the Seismic Site table, the Seismic Data table, and the Images table (Fig. 9). The one-to-many relationship between the

tables remains the same using the ArcGIS geodatabase relationship classes. These classes allow for the proper table relationships (cardinality) of data in the new feature classes.

In order to accomplish a one-to-many relationship between the Seismic Project table and the Seismic Site table, and between the Seismic Site table and the Seismic Data table, two relationship classes were created (Fig. 10). One relationship, named "P-S," is a one-to-many relationship between the Seismic Project table and the Seismic Site table, and uses project ID as the primary key field. A second relationship, named "S-V," is a one-to-many relationship between the Seismic Site table and the Seismic Data table, and uses seismic site ID as the primary key field.

Visualization and Analysis

Geographic coordinates in the Seismic Site table were used to create a point-type feature class named XY seismic site (Fig. 11). Each color on the map shown in Figure 11 represents a seismic site point that belongs to a project referenced in the Seismic Project table (one-to-many relationship). For easier visualization and querying of many

Seismic Project

	ID ▾	Project ID ▾	Project Nam ▾	Source Nam ▾	Click to Add ▾
⊞	1	1	Paducah	Harris	
⊞	2	2	Henderson	Higgins	
⊞	3	3	Purchase	Jackson	
⊞	4	4	Arkansas	Street	
⊞	5	5	Missouri	Street	
⊞	6	6	Tennessee	Street	
⊞	7	7	Maysville	Ting Li	
⊟	8	8	Memphis	Wood	

	ID ▾	Seismic Site ▾	Old Site ID ▾	Latitude ▾	Longitude ▾	Elevation(m ▾	Vs30(m/s) ▾	D
⊞	519	460	1	35.379	-90.03	68.6	198	
⊞	520	461	2	35.381	-90.066	70.1	200	
⊟	521	462	3	35.32	-90.05	105.2	272	

	ID ▾	LayerOrder ▾	From_m ▾	To_m ▾	Thickness_n ▾	Velocity_m_ ▾	MapUnit ▾
	68	1	0	10	10	192	
	69	2	10	43	33	344	
	70	3	43			494	
✳	(New)						

	ID ▾	Seismic Site ▾	Old Site ID ▾	Latitude ▾	Longitude ▾	Elevation(m ▾	Vs30(m/s) ▾	D
⊞	522	463	4	35.284	-90.049	91.5	0	
⊞	523	464	5	35.338	-89.954	76.2	220	
⊞	524	465	6	35.279	-89.942	73.2	223	
⊞	525	466	7	35.333	-89.89	83.8	0	
⊞	526	467	8	35.293	-89.846	77.7	270	
⊞	527	468	9	35.286	-89.762	76.2	216	
⊞	528	469	10	35.321	-89.667	82.3	252	

Figure 8. The four-table database structure in Microsoft Access. Data structure was based on a one-to-many relationship.

points, a polygon feature class was created to represent the area where data were collected. This new polygon was connected to the Seismic Project table and its seismic-site points (Fig. 12). By clicking on any site point or polygon on the map with the identify tool, the related data, such as the project information or the vertical soil layer data and velocity,

Contents | Preview | Description

Name	Type
P_S	File Geodatabase Relationship Class
S_V	File Geodatabase Relationship Class
Seismic_Project	File Geodatabase Table
Seismic_Project_	File Geodatabase Feature Class
Seismic_Site	File Geodatabase Table
ShearWaveVelocities	File Geodatabase Table
XYSeismic_Site	File Geodatabase Feature Class

Figure 9. The ArcGIS file geodatabase contains three tables, one point feature class, one polygon feature class, and two relationship classes.

can be identified. The data from these features can also be queried in ArcMap.

The weighted-average shear-wave velocity of the upper 30 m of soil-bedrock has been used to account for ground-motion site effects in the National Earthquake Hazards Reduction Program provisions (Building Seismic Safety Council, 1998, 2009). The Vs_{30} data in this database were used to create an interpolated map showing distribution of Vs_{30} values, using the kriging method in ArcGIS Toolbox (Fig. 13).

The classifications according to NEHRP are:
A. Hard rock with measured shear-wave velocity $Vs_{30} > 1,500$ m/s
B. Rock with 760 m/s $< Vs_{30} < 1,500$ m/s
C. Very dense soil and soft rock with 360 m/s $< Vs_{30} < 760$ m/s
D. Stiff soil with 180 m/s $< Vs_{30} < 360$ m/s
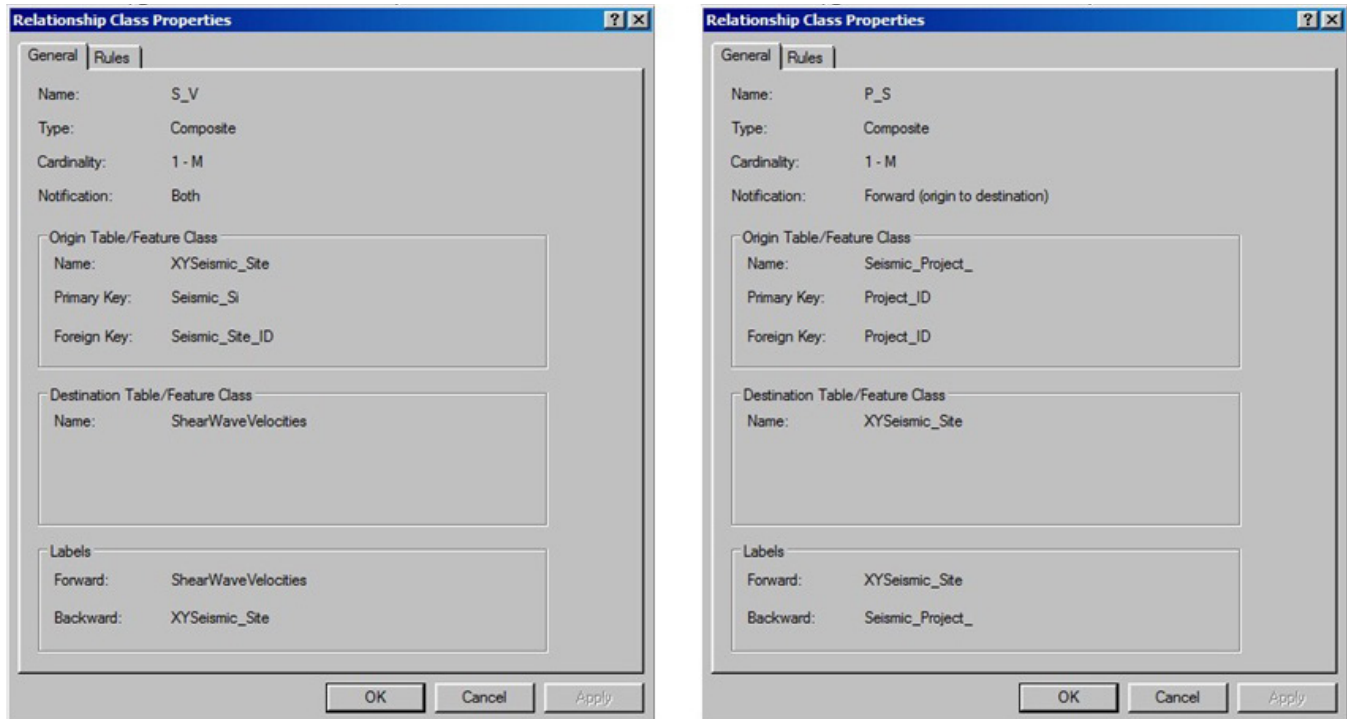E. A soil profile with $Vs_{30} < 180$ m/s

Figure 10. The relationship class properties. The relationship named "S-V" is a one-to-many relationship between the Seismic Site table and the Seismic Data table. The relationship named "P-S" is a one-to-many relationship between the Seismic Project table and the Seismic Site table.

Summary

Over the last 20 years, researchers at the University of Kentucky have collected seismic-reflection and -refraction data for characterization of seismic-velocity models of the soil-sediment overburden throughout the central United States. Managing these data and associated information has been difficult because of the lack of a centralized repository to assist storage, retrieval, and analysis. In order to make these data more accessible and manageable, Vance (2006) created an ArcGIS personal database. But because of inconsistencies with field names and data type, the original database was inadequate for seismic-hazard analysis.

In order to construct a new unified database for easier management, access, and use, Microsoft Access was used to design the data structure and field properties. The database was designed as four tables. The Seismic Project table is the source data, the Seismic Site table contains all the information related to the site, the Seismic Data table includes vertical soil-layer information, and the Images table contains attached documents and images. This four-table data design is connected by the project ID and seismic site ID fields.

Following the preliminary design of the database with Microsoft Access, an ArcGIS geodatabase was created so that the data could be visualized spatially. The data in the Access database were exported into the geodatabase, and the data structure and field properties were designed to match. New data can now be added to both the new Access database and matching geodatabase, improving GIS analysis and map creation. In addition, the geodatabase is compatible with existing KGS databases, and its data can be distributed via existing online map services in the future.
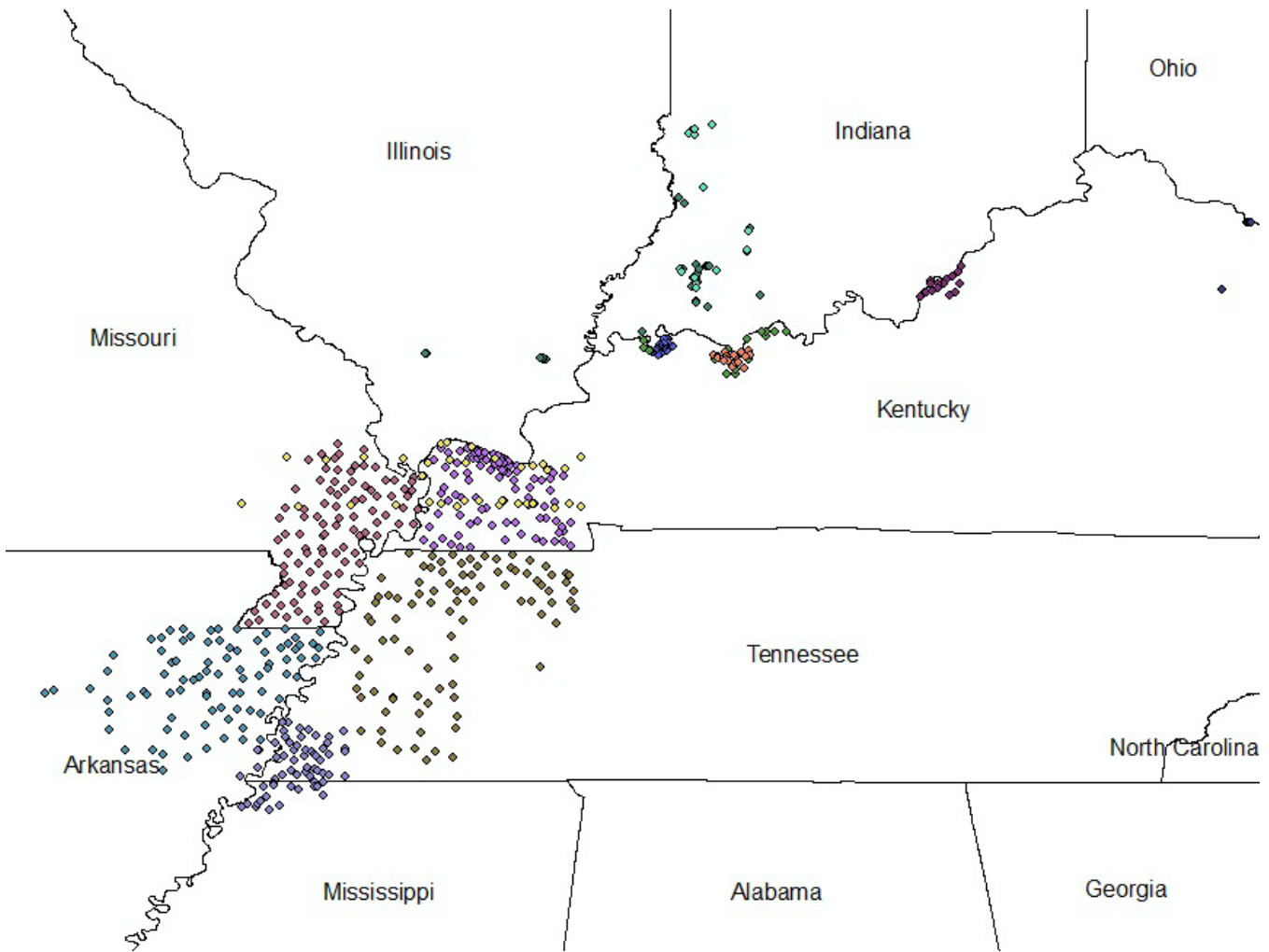
Figure 11. Locations of the XY seismic site feature class, which was created by the geographic coordinates in the Seismic Site table. It shows where the seismic data were collected and locations of site-correlated information such as Vs_{30}.

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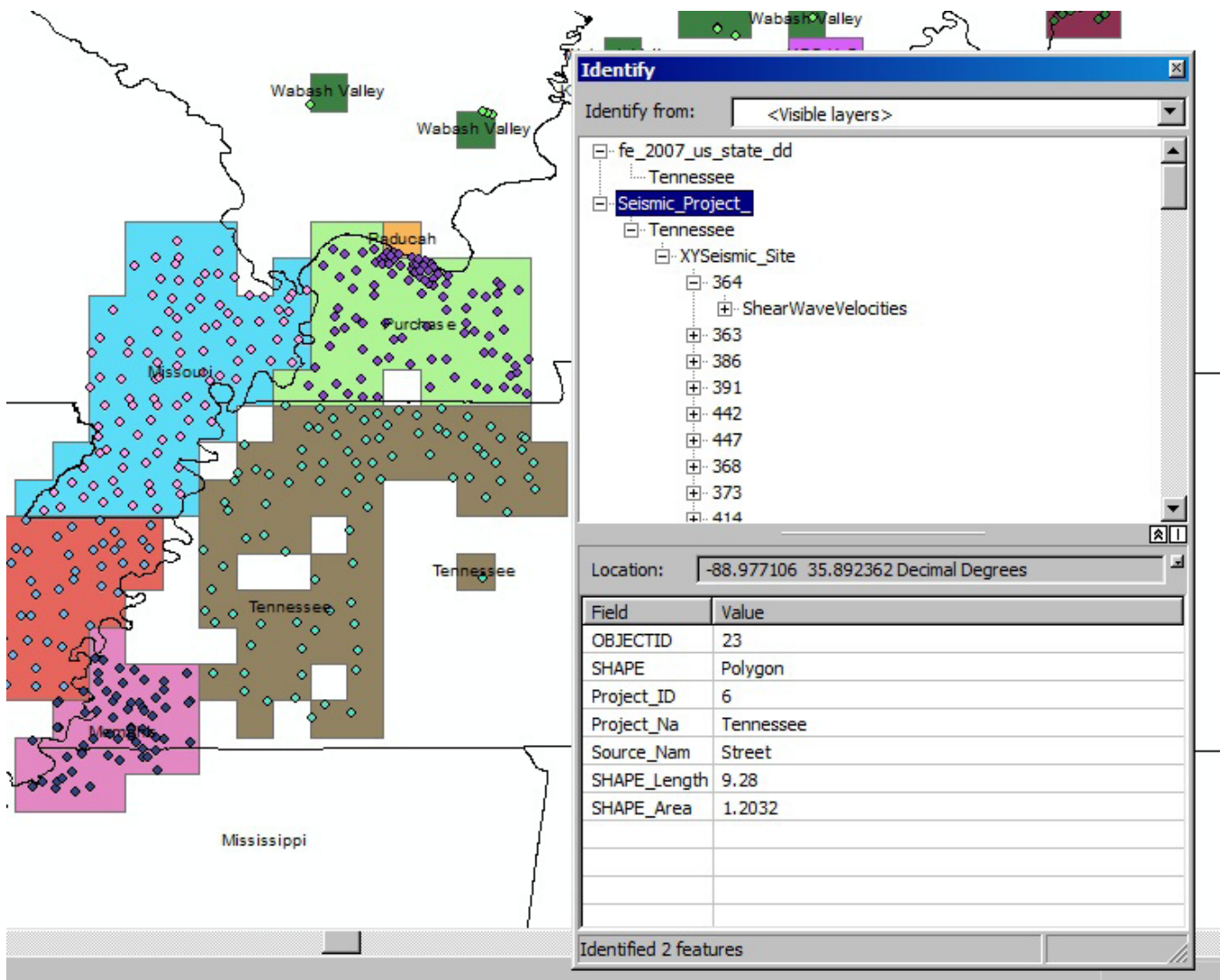Harris, J.B., 1992, Site amplification of seismic ground motions in the Paducah, Kentucky,

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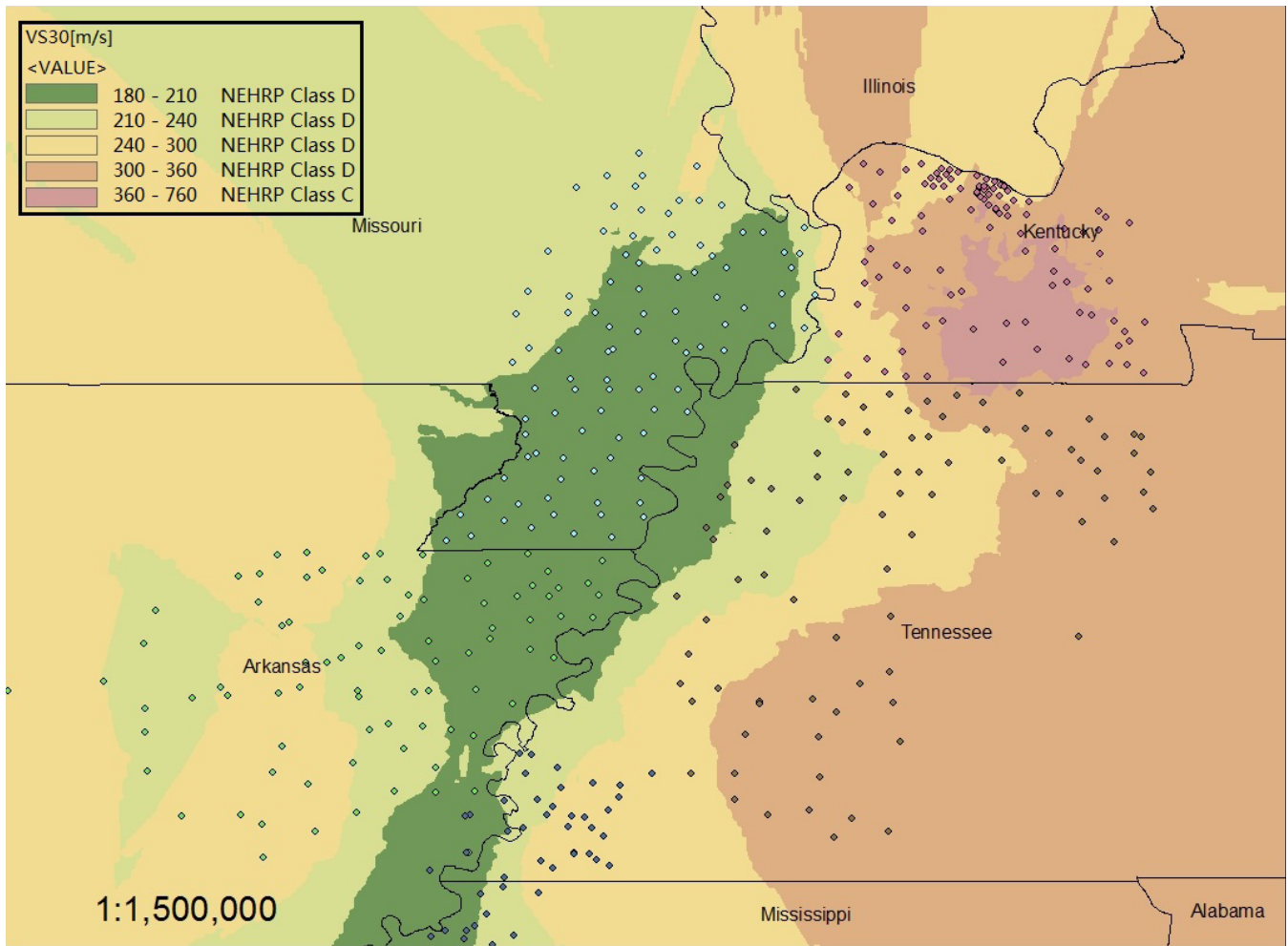
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