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Seismic Site Classifications for the St. Louis Urban Area

by Jae-won Chung and J. David Rogers

Abstract Regional National Earthquake Hazards Reduction Program (NEHRP) soil class maps have become important input parameters for seismic site characterization and hazard studies. The broad range of shallow shear-wave velocity (V_{S30}, the average shear-wave velocity in the upper 30 m) measurements in the St. Louis area results in significant uncertainties between the actual spot values and the averaged values used to assign NEHRP soil classes for regional seismic hazard studies. In the preparation of an NEHRP site classification map of the St. Louis urban area, we analyzed 92 shear-wave velocity (V_S) measurements, supplemented by 1400+ standard penetration test (SPT) profiles in areas bereft of V_S measurements. SPT blow counts correlated to V_S values based on the published correlations. The data were then compiled for respective surficial geologic units and bedrock type. These data suggest that the reciprocal of V_{S30} exhibits a fairly linear relationship with depth to bedrock, likely because V_{S30} is a function of the thickness of surficial materials exhibiting relatively low V_S values. The V_{S30} values were interpolated by summing the regressed V_{S30} on the depth to bedrock and kriged values of the regression residuals. The resulting NEHRP site classification maps predict that upland areas of the St. Louis area are spatially classified as soil site classes S_B to S_D, while the low-lying floodplains are consistently classified as S_D to S_F.

Introduction

The evaluation of seismic site conditions is commonly made by comparing the thickness of unconsolidated materials and shear-wave velocity (V_S) of these materials with that of the underlying bedrock, generally referred to as the impedance contrast. The intensity of seismic shaking tends to increase where sediments of low density and low V_S exist (Fumal and Tinsley, 1985). Site classifications for new construction are generally best resolved with site V_S testing of recognized surficial geologic units. Previous studies have demonstrated that the average V_S in the upper 30 m (V_{S30}) is inversely correlated with the average horizontal spectral amplification of earthquake ground motion (Borcherdt and Gibbs, 1976; Borcherdt *et al.*, 1991). To assess the susceptibility to ground amplification, in 1994 the National Earthquake Hazards Reduction Program (NEHRP) defined six soil profile types (S_A to S_F) following the study by Borcherdt (1994), which suggested a consistent relationship between site response and V_{S30} (Building Seismic Safety Council [BSSC], 2003; R. Borcherdt, personal comm., 2008). The six site classes, defined in terms of V_{S30}, are described in Table 1.

Site-Conditions Mapping Method

The fundamental complication in estimating seismic site response in urban environments of considerable land area (> 1000 km^2) is that V_S values are measured at discrete points (due to cost, permission, and space constraints), and a method of interpolating these measurements generally requires the employment of some assumptions. One of the fundamental assumptions is that V_S values depend on the physical properties of materials. This arose from early studies that sought to correlate V_S data with surficial geology and/or late Quaternary stratigraphy and then interpolate those (Tinsley and Fumal, 1985; Park and Elrick, 1998; Wills *et al.*, 2000; Stewart *et al.*, 2003). Most of these studies were performed in California and were consistent in showing a significant correlation between geologic age and V_S, because of increased cementation with age.

Holzer, Bennett, *et al.* (2005) produced an NEHRP site condition map of the central San Francisco Bay (140 km^2) using 210 V_{S30} values, which were derived from the average V_S values for surficial geologic units and their estimated thicknesses. It is noted, however, that this approach would be difficult to apply for larger areas (Wills *et al.*, 2006), because it might require a much larger pool of V_S measurements, as well as the accurate thickness of each stratigraphic unit. These variables are seldom known with any significant reliability over broad areas, especially if the stratigraphic horizons are more than 20 m deep (because far fewer wells or borings penetrate the deeper horizons). This approach also tends to ignore variations of V_S with depth. The regional site conditions have generally been delineated according to the arithmetic mean of the V_{S30} values for the surficial geologic

Table 1
NEHRP Site Classification (BSSC, 2003)

Site Class	V_{S30} (m/s)	N_{30}	General Description
S_A	> 1500	N.A.	Hard rock
S_B	760–1500	N.A.	Rock with moderate weathering
S_C	360–760	< 50	Very dense soil and soft rock
S_D	180–360	15–50	Stiff soil
S_E	< 180	< 15	Soft clay soil
S_F	N.A.	N.A.	Soils requiring site-specific evaluations

unit and their corresponding NEHRP site classes (Borcherdt *et al.*, 1991; Borcherdt, 1994; Wills *et al.*, 2000; Wills and Clahan, 2006). As a consequence, this method implies that areas lying upon the same surficial geologic units would be designated as the same NEHRP site class.

Uncertainty of NEHRP Site Classes Assignments

Our previous compilation of V_{S30} site-conditions (Chung, 2007) for the St. Louis metro area suggested considerable variance and an uneven distribution of V_{S30} data, including

- The wide distribution of V_{S30} values within mapped units exists between the NEHRP site class categories. Outlier values of V_{S30} were occasionally identified, which tend to affect the overall average of V_{S30} values, shifting a unit's assignment to the next higher soil site class (Fig. 1a).
- The average value of V_{S30} assigned to a specific unit is often within ±20 m/s of the designated site class boundaries (Fig. 1b, c).
- Very few V_S tests were carried out on alluvial fan facies, and these were classified as zones S_E ($V_{S30} < 180$ m/s) and S_D (V_{S30} 180–360 m/s; Fig. 1c). If more tests had been taken in these spatially-restricted materials, we could expect the average values to favor either one site class or the other.

The variability of V_{S30} within the surficial geologic units is likely attributed to (1) natural variations in stratigraphy, the depth to rock horizons, and the range of sedimentation (Bauer *et al.*, 2001; Romero and Rix, 2001; Gomberg *et al.*, 2003; Holzer, Padovani *et al.*, 2005); (2) misclassification of these same units by using increasingly inaccurate geologic maps of smaller scale (Park and Elrick, 1998; Wills and Clahan, 2006); or (3) the result of human interpretation and/or instrumental errors (Scott *et al.*, 2006; Bauer, 2007). These factors often result in significant uncertainties between the actual V_{S30} values and the averaged values used to assign NEHRP soil classes in regional seismic hazard studies, which can lead to erroneous site-condition maps. Wills *et al.* (2000) found that 25% of V_S sites within California were misclassified. These problems imply that the mapped units can be assigned with multiple NEHRP site classes.

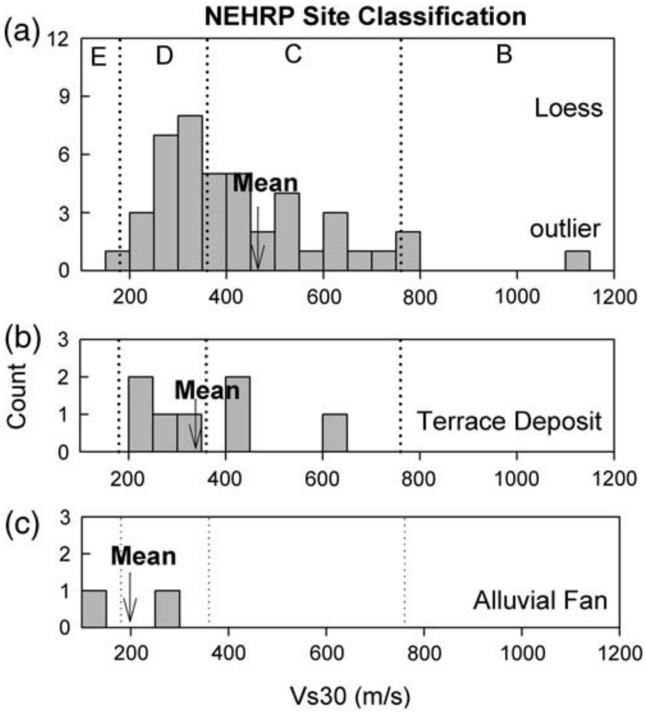

Figure 1. Histograms of V_{S30} values within the surficial geologic units blanketing the St. Louis area showing (a) the wide distribution of V_{S30} values and outliers, (b) instances where the mean V_{S30} values fell on the border between NEHRP site class boundaries, and (c) an inadequate number of V_S tests to adequately assess the alluvial fan unit.

In the St. Louis area study, we employed the following procedures:

1. Analyze V_S profiles, as well as standard penetration test (SPT) profiles. The SPT profiles are less accurate but allow us to fill in areas bereft of reliable V_S measurements. They are also helpful in identifying anomalous outliers, which may be due to buried bedrock knobs or measurement errors.
2. Identify observable relationships between V_{S30} values and the respective depths to bedrock, in order to characterize the variance of V_{S30} with bedrock depth.
3. Prepare detailed regional NEHRP site classification maps, using V_{S30} estimates. For this step, we used 92 V_{S30} measurements and more than 1400 SPT profiles (taken from engineering borings), surficial and bedrock geologic maps, and the depth-to-bedrock maps.

Study Area

Geologic Setting and Earthquake Hazards

The study area encompasses 12 U.S. Geological Survey (USGS) 7.5 minute quadrangles (a land area of 1800 km^2) in the greater St. Louis area, Missouri, and Illinois (Fig. 2). This area is located on Quaternary deposits, which consist of (1) Holocene alluvial deposits in major channels (Mississippi,

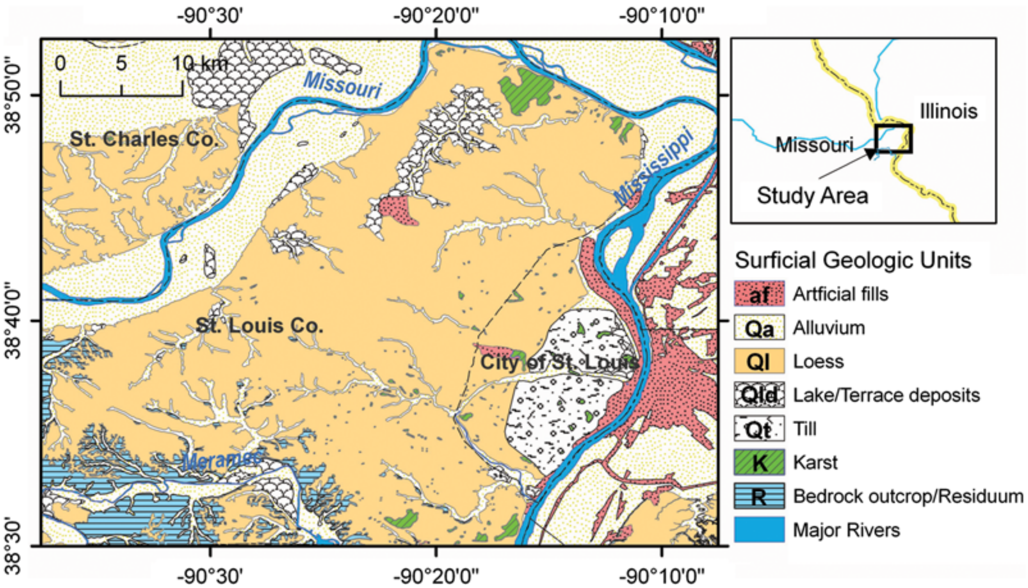

Figure 2. Map of the St. Louis area showing generalized surficial geology (adapted from Schultz, 1993; Grimley and Phillips, 2006; and Grimley, 2009). The color version of this figure is available only in the electronic edition.

Missouri, and Meramec Rivers) or stream valley floodplains, and (2) Pleistocene loess and/or glacial till deposits mantling dissected uplands. These Quaternary sediments overlie Paleozoic strata of Pennsylvanian rocks (dominantly shales and some sandstones), Mississippian rocks (mostly limestones with some shale), or older Paleozoic limestones, which dip gently toward the east (Harrison, 1997). Information gleaned from the engineering borings in this region indicate that the Quaternary deposits are generally about 30 to 40 m thick in the floodplains and 5 to 15 m thick in the dissected uplands.

Earthquake hazards in the midwest are significantly influenced by the severity of the impedance contrasts between dense bedrock strata and the overlying unconsolidated soil cap. Shaking intensity is also exacerbated by extremely low damping of seismic energy across the central and eastern United States (CEUS), because the exposed Paleozoic rock is relatively dense and unfractured (Bolt, 1993). The Quaternary deposits thicker than about 15 m magnifies ground shaking (Rogers *et al.*, 2007). The St. Louis region has experienced strong ground shaking as a result of prehistoric and contemporary seismicity associated with the Wabash Valley and New Madrid Seismic Zones (McNulty and Obermeier, 1999; Tuttle *et al.*, 1999). The Federal Emergency Management Agency (FEMA, 2008) has estimated an annualized expected loss of $58.5 million for this densely populated urban area ($2.8 million in 2010). In 2004 the USGS organized the St. Louis Area Earthquake Hazards Mapping Project (SLAEMHP). A technical working group (TWG) consisting of earth scientists and engineers guide this project in preparing earthquake hazard maps (Williams *et al.*, 2007; Karadeniz *et al.*, 2009).

Preparation of NEHRP Site Classes

The City of St. Louis, St. Louis County, and St. Charles County in Missouri adopted the 2003 International Building Code in 2006, which includes the 2000 NEHRP provisions incorporating soil profile type to estimate ground motion loads for earthquake-resistant building design. Bauer *et al.* (2001) prepared a map portraying seismic shaking potential for the high-risk areas in five midwestern states bounding the New Madrid seismic zone at a scale 1:250,000. Because of the lack of actual measurements in the St. Louis area, V_S values for the geologic units and their respective thicknesses were assumed based on V_S measurements of similar units measured elsewhere in the Midwest, which exhibit a remarkably consistent trend with depth of burial, not with geologic age (Bauer, 2007). An NEHRP site class was then assigned for the combined soil cap. The resulting map provides a rough estimate of the soil site classes, which mimic the areal limits of the active floodplains and are generally classified as S_F (liquefiable soil), while the uplands were classified as S_C (360 to 760 m/s in V_{S30}) or S_D (180 to 360 m/s in V_{S30}).

Data Acquisition

The input data for mapping NEHRP site classification in this study consist of the following components:

- The Quaternary surficial geologic maps (Fig. 2) were collected from (1) the USGS (Schultz, 1993) and (2) the Illinois Geological Survey (ISGS; Grimley and Phillips, 2006; Grimley, 2009). Bedrock geologic maps (Fig. 3) were compiled from the publications of the USGS (Harrison, 1997) and the ISGS (Kolata, 2005). Different mapping styles have traditionally been employed by Missouri

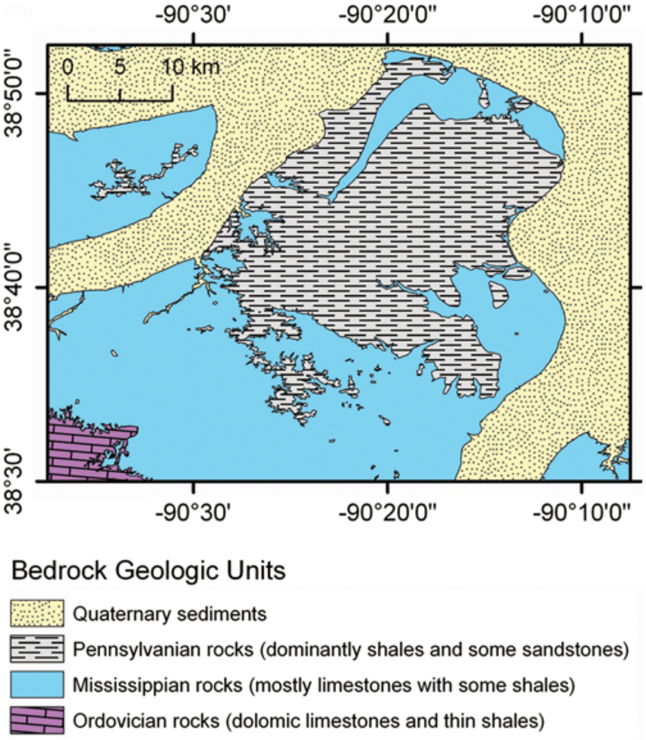

Figure 3. Simplified bedrock geological map of the St. Louis area (adapted from Harrison, 1997, and Kolata, 2005). The color version of this figure is available only in the electronic edition.

(depositional models) and Illinois (formational models). These contrasting styles were unified for this study based on sediment types and genesis (Chung and Rogers, 2010).

- V_S profiles were measured at 92 sites (Fig. 4) and provided to our study team by the Missouri University of Science and Technology (D. Hoffman, personal comm., 2007; Hoffman *et al.*, 2008), the USGS (Williams *et al.*, 2007; R. Williams, personal comm., 2007), and the ISGS (Bauer, 2007; R. Bauer, personal comm., 2007). These velocity profiles were obtained from multichannel analysis surface waves (MASW), refraction/reflection, and downhole measurements, respectively.
- The logs of 1428 engineering boreholes (Fig. 4) including soil/rock descriptions, respective thickness, and SPT blow counts (N values) were included. These were collected from the Missouri Division of Geology and Land Survey (MODGLS; Palmer *et al.*, 2006), the ISGS, and other agencies. Most of these borings are sampled between 0.76-m and 1.5-m intervals in depth. These borehole data were used to calculate SPT-based V_S values.
- The map of depth to bedrock was prepared using ordinary kriging for the upland and polynomial regression for the floodplains (Fig. 5; Chung and Rogers, 2012). This map employed 4838 data points, which include V_S and SPT sites, and additional well logs collected from MODGLS (2007).

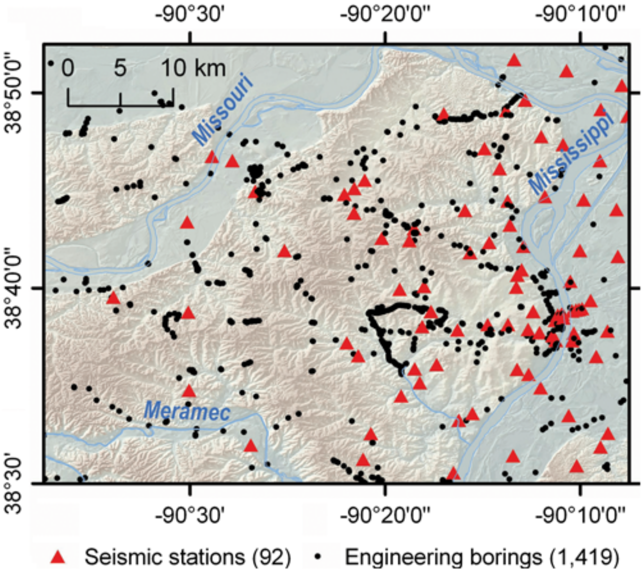

Figure 4. Map showing the locations of V_S profiles and engineering borings with SPTprofiles. The color version of this figure is available only in the electronic edition.

Estimation of V_S and V_{S30}

The SPT is widely employed to obtain a sample of the soil being tested and describe soil behavior due to its simplicity and low cost (Rogers, 2006). The SPT-N values are proportional to V_S values, because the standard penetration resistance relies on bulk density, effective stress, sediment thickness, and void ratio. Thus, SPT profiles can serve as proxy to estimate V_S of soil and as another parameter to assign the soil site class, where the V_S is not available or insufficient detail exists to ascertain the site class categories (Sykora and Stokoe, 1983; Fumal and Tinsley, 1985; BSSC, 2003). The SPT procedure is good for measuring the resistance of granular soils and detecting/conforming layered materials, such as varved soils. However, SPT results are more impacted by equipment quality and operator experience, which often lead to overestimating blow counts, especially when penetrating gravelly materials or soft soil horizons lying above much stiffer materials (Youd *et al.*, 2001; Rogers, 2006).

An equivalent method of averaging SPT-N values to a 30-m depth (Table 1, N_{30}) to evaluate site classification was not used in this study. Our preliminary analysis reveals that the N_{30} values generally lead to softer site classes than V_{S30}-based site classes, likely due to a low N value being assigned for hard rock (100 blows/ft), and V_{S30} cannot be interpolated from N_{30}. Instead, we estimated V_S values using the stratigraphic descriptions and the SPT blow counts encountered as a function of depth.

V_S Values of Bedrock

We gathered information on accepted V_S values of Pennsylvanian and Mississippian rocks in the St. Louis area, including the V_S measurements made on bedrock for this

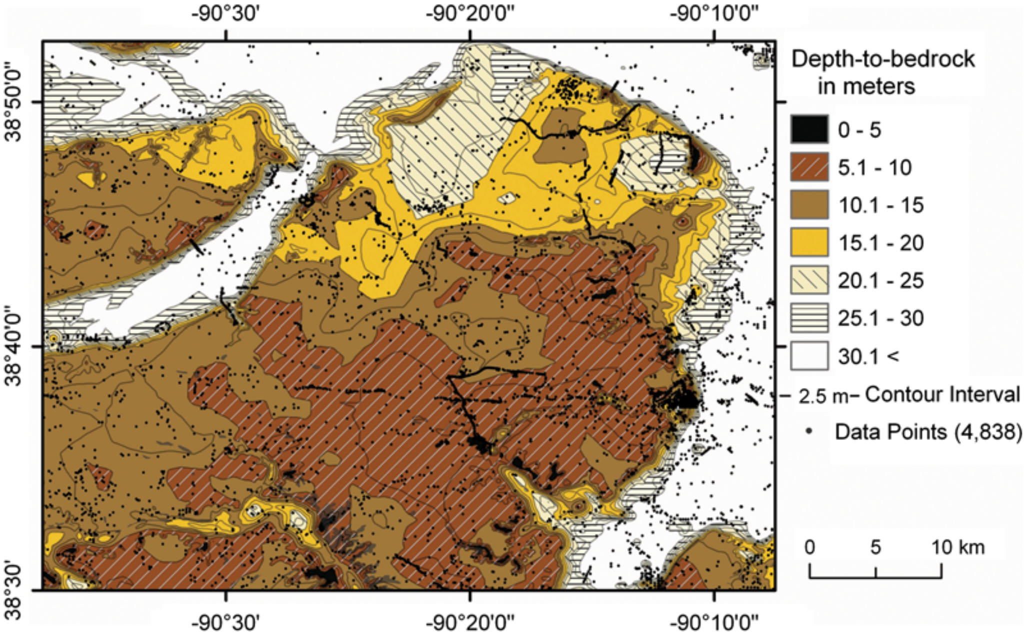

Figure 5. Map showing the depth to bedrock in the St. Louis area. The color version of this figure is available only in the electronic edition.

study and other studies, such as Bauer *et al.* (2001) and Bauer (2007), and SLAEMHP-TWG meetings (held in 2007). Based on V_S values derived from these sources, we assumed that the bedrock V_S values range from 1000 to 2200 m/s for unweathered strata and from 600 to 1120 m/s for the weathered strata (Table 2). These values were used to estimate the V_S of bedrock in the zone between the ground surface and a 30-m depth, where no measurements could easily be made.

SPT-Based V_S

The published literature reports numerous correlations between uncorrected SPT-*N* values and V_S. After initially applying some of these relationships for eight sites within the St. Louis area, where both V_S and SPT profiles were coincidently collected, we found that the correlation proposed by Ohta and Goto (1978) gave the best correlation coefficient ($r = 0.87$) and produced the closest SPT-based estimates to the measured V_S values (differences < 20 m/s; Fig. 6). The statistical correlation for all soils using the Ohta and Goto (1978) method is given as

$$V_S = 85.34N^{0.348} \quad \text{for all soils.} \tag{1}$$

The V_{S30} values estimated from SPT-based V_S correlations and the assigned bedrock V_S values (shown in Table 2) exhibit similar values (differences < 15 m/s for V_{S30}). The measured V_{S30} values (Fig. 6) also showed high correlation coefficients ($r = 0.99$ for V_{S30}). These results suggests that (1) the SPT-*N* value is an appropriate estimator to

Table 2
Assigned V_S for Materials

Material Type	V_S (m/s)
Soil	$85.34N^{0.348}$*
Pennsylvanian Rocks	
Weathered (0.5 to 5.5 m thick)	600
Moderate to hard	1,000
Mississippian Rocks	
Weathered (0 to 2.5 m thick)	1,120
Moderate to hard	2,200

**N* is SPT (standard penetration test) blow counts.

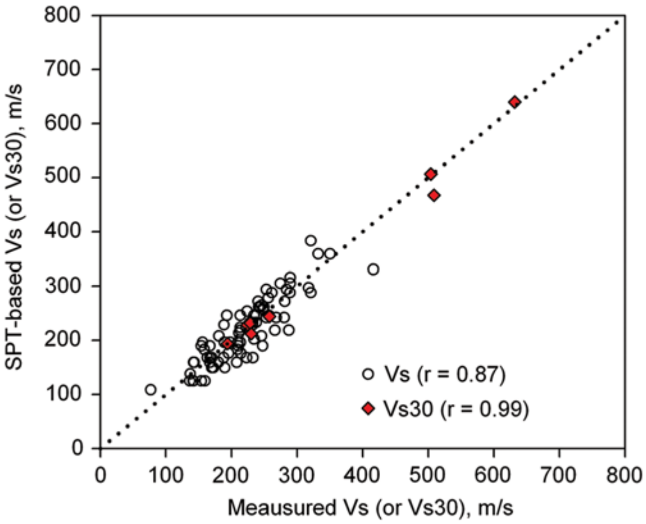

Figure 6. Plot of measured versus estimated V_S and V_{S30} in the St. Louis urban area: *r* is the correlation coefficient. The color version of this figure is available only in the electronic edition.

approximate V_S values, and (2) SPT-based V_S and the assigned bedrock V_S values offer a fairly reliable means to estimate V_{S30} values at unmeasured sites.

Interpolation of V_{S30}

V_{S30} values derived from direct measurements and SPT profiles were computed by time-averaging V_S in the upper 30 m, using equation (A1). These V_{S30} sites were grouped by the respective surficial geologic units upon which they were performed. There is a wide range of V_{S30} within most of the mapped units (e.g., generally $180 \sim 650$ m/s for alluvium-covered areas; $250 \sim 850$ m/s for loess-covered areas). These ranges tend to straddle some of the NEHRP classification boundaries (e.g., S_E to S_C for alluvium-covered areas; S_D to S_B for loess-covered areas). The wide range of V_{S30} values may result from thickness differences of the soft sediments, which tend to influence V_{S30} values (Fumal and Tinsley, 1985; Williams *et al.*, 2007; Haase *et al.*, 2011), because the slowness-averaging method used to calculate V_{S30} tends to skew V_{S30} toward the lower V_S values exhibited by soft soils (Brown *et al.*, 2002; Holzer, Padovani, *et al.*, 2005). This suggests that V_{S30} values vary according to (1) the V_S values of soft sediments; (2) the thickness of the mapped unit (sediment package), or depth to bedrock; and (3) the V_S value of bedrock, especially when it lies near the ground surface.

V_{S30} versus Depth to Bedrock

To better understand and examine the variation of V_{S30} within the surficial geologic units and interpolate these data, we propose a method of mapping V_{S30} for the sediment package (depth to bedrock), which we found was the single-most important factor influencing the slowness-averaging method for calculating V_{S30}. V_{S30} tends to decrease with increasing thickness of the sediment package (soil cap). The depth to bedrock can be employed to estimate V_{S30} based on the statistical relationships between V_{S30} and bedrock depth. Given the observation that (1) V_S values of unconsolidated geologic units are nearly constant or increase slightly with depth (Holzer, Bennett, *et al.*, 2005; Bauer, 2007), and (2) the average V_S over any depth interval varies depending on depth to bedrock (Fumal and Tinsley, 1985), we assumed that sites on specific surficial geologic units were likely to exhibit similar physical characteristics and, therefore, possess similar V_S values with depth, but not in situations where bedrock knobs may exist (Fig. 7).

Based on equations (A1) and (A4) showing that V_{S30} is inversely proportional to bedrock depth, we plotted $(V_{S30})^{-1}$ values versus the corresponding bedrock depths to evaluate their linear relationship. V_{S30} values exhibited little correlation with bedrock depth intervals greater than ~30 m. These data points were excluded from the correlations in the major river floodplains. The data plots suggest that bedrock depths when appraised by the surficial soil unit and bedrock type exhibit a fairly linear relationship with $(V_{S30})^{-1}$ values.

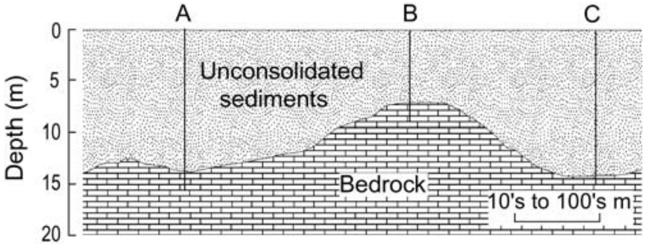

Figure 7. Influence of the depth to bedrock on physical properties of the overlying sediment package. SPT sampling at A and C will tend to yield similar results, but those at position B will exhibit increased blow counts (resistance) at similar depth intervals because of the proximal influence of the unyielding soil–bedrock interface.

An empirical relation (equation A5) can be derived from the simple linear regression of $(V_{S30})^{-1}$ from bedrock depth by the surficial soil unit and bedrock type, shown on the example graphs for alluvium (Fig. 8). Linear regression analyses for the surficial soil units and bedrock type are summarized in Table 3. The high coefficients of determination of regression ($R^2 > 0.80$) for the surficial soil units and bedrock type shown in Table 3 indicate that the bedrock depth can be used as a reasonable estimator of V_{S30}. By using the regression equations, the V_{S30} values can be estimated for known or assumed bedrock depths; for example, the V_{S30} is expected to be approximately 760 m/s (the upper boundary of S_C) or 360 m/s (the upper boundary of S_D) wherever loess deposits (Ql) overlie Mississippian limestone at 5-m or 14-m depths, respectively.

Mapping NEHRP Site Classes

The V_{S30} values in the area of bedrock depth shallower than 30 m were initially estimated using linear regression of

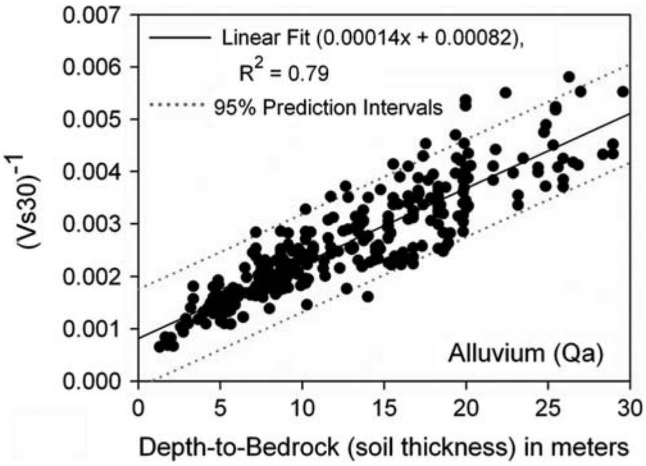

Figure 8. Plots comparing $1/V_{S30}$ versus depth to bedrock and the linear fit with 95% prediction bands. R^2 is the coefficient of determination.

Table 3

Linear Regression Coefficients for $1/V_{S30}$ Values for a Given Bedrock Depth

Surficial Geologic Unit	Bedrock Type	Slope	Intercept	R^2 *	No. of Data Points
Artificial fills (af)	Pennsylvanian or Mississippian rocks	0.00015	0.00081	0.81	103
Alluvium (Qa)	Pennsylvanian or Mississippian rocks	0.00014	0.00082	0.79	380
Loess (Ql)	Pennsylvanian rocks	0.00015	0.00105	0.81	560
	Mississippian or older age rocks	0.00016	0.00052	0.86	290
Lake deposits (Qld)	Pennsylvanian or Mississippian rocks	0.00016	0.00076	0.80	121
Glacial till (Qt)	Mississippian rocks	0.00014	0.00082	0.88	57
Residuum (R)	Mississippian or older age rocks	N.A.	N.A.	N.A.	9

*R^2 is the coefficient of determination.

each geologic unit on the contour map of bedrock depth. Then, in order to honor the actual V_{S30} values at sampled sites, the regressed values were adjusted with the ordinary kriging map of the residuals. The V_{S30} values of the area of bedrock depths deeper than 30 m were separately evaluated using ordinary kriging with a spherical model. These procedures were used to provide final estimates of V_{S30} in the St. Louis study. The NEHRP site classes were then assigned according to the V_{S30} values (Fig. 9).

The resultant NEHRP site classification maps show that (1) alluvium (Qa) in most areas was assigned class S_D and, in just a few areas, site class S_E; (2) loess (Ql) was assigned to site classes S_B, S_C, and S_D where it is underlain by Mississippian limestone at shallow depth, Mississippian limestone, and Pennsylvanian shale, respectively; (3) lake or terrace deposits (Qld) were assigned to soil site class S_D; and (4) glacial till (Qt) was assigned soil site class S_C (Fig. 9).

No V_S or SPT measurements were made on bedrock outcrops in the study area. We consider the Paleozoic age bedrock to be site class S_B (rock with weathering) based on weathering and open joints observed in the exposures (Lutzen and Rockaway, 1971; Stinchcomb and Fellows, 2002). Site class S_A (hard rock) was not used in this study.

Only nine SPT boring logs were available for the weathered residuum (1 ~ 10 m thick), which generally consist of clay, silt, and sand derived from the decomposition of underlying bedrock (Schultz, 1993). The value of SPT-based V_{S30} in the residuum ranges from 560 to 1080 m/s, resulting in a mean value of 650 m/s with a standard deviation of 170 m/s. The small sample size of this dataset resulted in broad confidence intervals of regression analysis with less predictive reliability (Helsel and Hirsch, 2002). We assigned this unit to site class S_B to S_C (very dense soil and soft rock), based on physical descriptions and SPT-based V_{S30} values.

Discussion and Conclusions

Our approach for assessing NEHRP soil site classes on regional planning maps employs different methodologies from previous studies in California, which have correlated each site class with the mean V_{S30} value of a surficial geologic unit, or to compile assigned V_S values to a 30-m depth. This study used V_{S30} values directly and supplemented derived V_{S30} values from SPT profiles in areas bereft of V_S measurements. Derived V_{S30} values were determined from the depth to bedrock for each mapped surficial soil unit and bedrock type. The data suggest that V_{S30} values vary

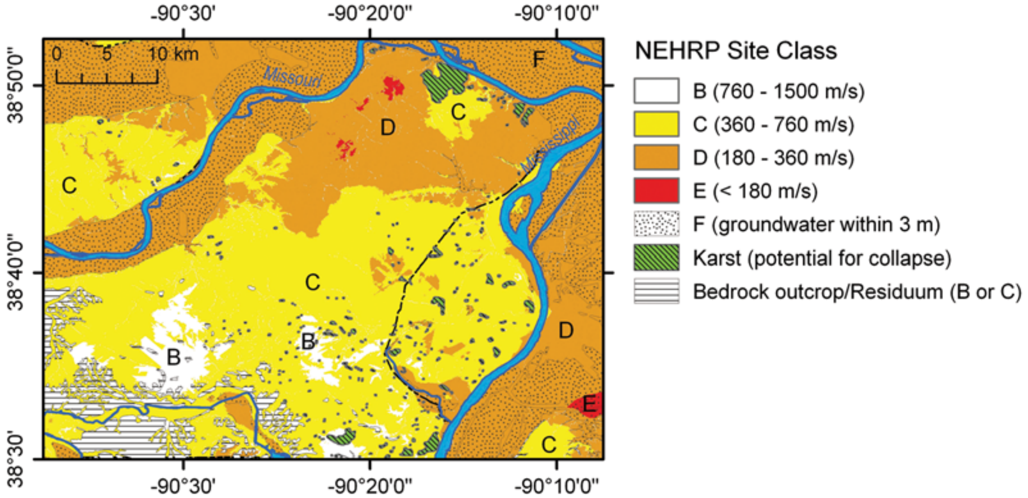

Figure 9. Map showing NEHRP soil site classifications for the St. Louis area. The color version of this figure is available only in the electronic edition.

markedly, according to the unit thickness and/or depth to bedrock. Because of this, NEHRP soil site classes could not be assigned according to unit age or stratigraphy alone but are consistently a function of depth (confinement) more than any other single factor.

Uncertainties

We propose a new method to interpolate V_{S30} in the CEUS by examining the fundamental relationships between V_{S30} values and the depth to bedrock (see Fig. 8, which illustrates the statistical trends of the entire data set). The statistical model leads to model uncertainty and does not explain the individual variation in V_{S30}, which is likely attributed to the natural variation in stratigraphy and/or the result of measurement error. To predict the variability of the unsampled data from the distribution of sampled data, we employed prediction intervals that reflect the uncertainty of the statistical model and the variability of single data points.

The regression analysis with 95% prediction intervals is shown on the example graph (Fig. 8). The regional NEHRP site class maps with 95% prediction intervals show that compared to the site class designation (Fig. 9), the NEHRP class was downgraded or upgraded in the lower or upper bound of the prediction interval map (Fig. 10), respectively. These prediction interval maps designate alluvium (Qa) as site class S_E to S_D; lake deposits (Qld) as site class S_E to S_D; loess (Ql) as S_D to S_B; and till (Qt) as S_D to S_B.

NEHRP Site Class F

Seismically-induced liquefaction usually occurs when the pore pressure of saturated sediments of low density and near zero cohesion exceeds the effective stress acting upon the material, allowing it to lose shear strength and behave as a fluid until sufficient drainage occurs to dissipate the elevated pore water pressure (Norris *et al.*, 1998; Wills and Hitchcock, 1999). Alluvium in the river valley floodplains of the St. Louis area may have liquefied during 1811–1812 New Madrid earthquakes (Tuttle *et al*, 1999; Tuttle, 2005), even though these quakes emanated from distances of ~250 km. Chung and Rogers (2011a, b) evaluated the channel alluvium ascertaining that it poses a significant liquefaction risk during a design earthquake (M 7.5 with a peak ground acceleration of 0.20 g), if the groundwater table is 3.5 m or less (the mean groundwater depth is just 0.7 m in much of the Mississippi River floodplain). For these reasons, the channel alluvium was conditionally designated soil class S_F in the study area (Figs. 9 and 10).

Remarks

The proposed technique may serve as a useful tool for estimating regional NEHRP soil site classes (for planning purposes) in other parts of the CEUS where similar geologic conditions exist, which are quite different from California. This method assumes that the V_{S30} values can be estimated for regional studies using the recognized (mapped) surficial units and depth to bedrock. The V_{S30}-based site conditions in similar geologic settings and bedrock depths are expected to be similar, based on correlations taken across all of the CEUS at sites along major rivers.

This method, for regional planning use, may have more error in assessing site class in areas where the depth to bedrock varies markedly over short intervals (escarpments, bedrock knobs, or depressions) or where physical properties vary laterally, such as the alluvial fans being dumped onto the major floodplains from local watercourses (like the Cahokia fans along the eastern side of the Mississippi floodplain). V_S procedures should be the preferred method for determining site class for design purposes. Direct V_S testing to determine site class is even more important to estimate seismic response in such areas, as well as the floodplain margins, where the depth to bedrock changes markedly along natural escarpments. Karst features, such as sinkholes, caverns, and closed depressions, are common to the Mississippian limestone and overlying soils. They exhibit an irregular and unpredictable

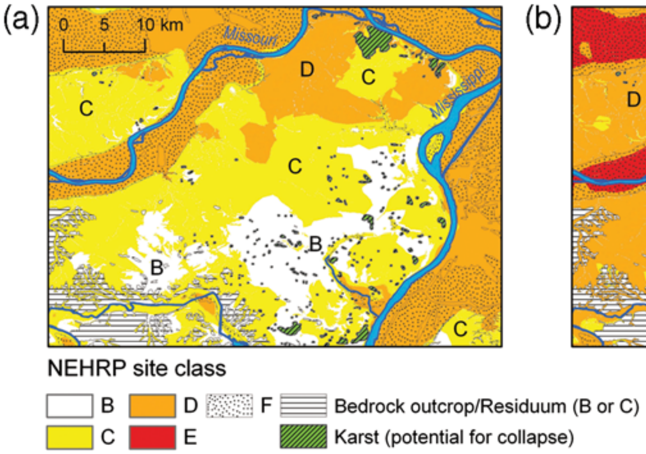

Figure 10. Maps showing NEHRP site classification with 95% prediction intervals: (a) the upper bound map and (b) the lower bound map. The color version of this figure is available only in the electronic edition.

bedrock surface, often composed of pinnacles and deep bedrock valleys. Karst features are vulnerable to potential ground failure, and collapse can be triggered by seismic shaking (Hoffman, 1995; Nuclear Regulatory Commission, 2007). Site-specific investigations would be needed to evaluate site conditions and associated seismic hazards in such cases.

Data and Resources

The ISGS surficial geologic maps can be obtained at their website (www.isgs.illinois.edu/maps-data-pub/ipgm.shtml, last accessed May 2009). SPT data were collected by the ISGS and are available at www.isgs.illinois.edu/sections/gru/wellmaps.shtml (last accessed June 2010). Borehole logs collected by the USGS (C. Watkins, personal comm., 2011) that were provided by private sector consultants are proprietary, while those supplied by public agencies are not restricted. All other data used in this paper came from published sources listed in the references. The data used in this paper were compiled for the USGS SLAEHMP. Data calculation and regression analyses were performed using Microsoft Excel (2007) and Analyze-it (2011), respectively. Data plots and kriging maps were generated using ArcGIS software V. 9.1.

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Appendix

The description of site classes defined in terms of V_{S30} in accordance with NEHRP provisions is shown in Table 1. The weighted average V_S to a 30-m depth (V_{S30}) is obtained using the following equation:

$$V_{S30} = \frac{30\ \text{m}}{\sum_{i=1}^{n} \frac{d_i}{V_{Si}}}, \tag{A1}$$

where d_i is the thickness of any layer between 0 and 30 m, and V_{Si} is the shear wave velocity (m/s). If

$$\sum_{j=1}^{a} d_j < 30\ \text{m}, \qquad \sum_{j=1}^{a} d_j + \sum_{k=1}^{b} d_k = 30\ \text{m}, \tag{A2}$$

where d_j is for soil layers ($\sum_{j=1}^{a} d_j$ is soil thickness or depth to bedrock), and d_k is for rock layers ($\sum_{k=1}^{b} d_k$ is for rock thickness to 30 m). Rearranging equations (A1) and (A2), equation (A1) can be written as

$$(V_{S30})^{-1} = \frac{1}{30\ \text{m}} \left(\sum_{j=1}^{a} \frac{d_j}{V_{Sj}} + \sum_{k=1}^{b} \frac{d_k}{V_{Sk}} \right), \tag{A3}$$

where V_{Sj} is for soil layers, and V_{Sk} is for rock layers. V_{Sk} is constant, in general, and thus

$$(V_{S30})^{-1} = \frac{1}{30\ \text{m}} \left[\sum_{j=1}^{a} \frac{d_j}{V_{Sj}} + \frac{(30\ \text{m} - \sum_{j=1}^{a} d_j)}{V_{Sk}} \right]. \tag{A4}$$

Using equation (A4) and the example data shown in Figure 7, a simplified equation can be empirically derived from the relationship between V_{S30} and the depth to bedrock (soil thickness);

$$(V_{S30})^{-1} = \beta_1 \mathrm{DTB} + \beta_0, \tag{A5}$$

where DTB is the depth to bedrock, β_1 is the regression coefficient, and β_0 is the intercept. The results of linear regression analysis for a surficial geologic unit are shown in Table 3.

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