A technical note on seismic microzonation in the central United States

Zhenming Wang

Kentucky Geological Survey, University of Kentucky, Lexington, Kentucky 40506, USA.
e-mail: zmwang@uky.edu

Microzonation is an effort to evaluate and map potential hazards found in an area, urban area in particular, that could be induced by strong ground shaking during an earthquake. These hazards include: ground motion amplification, liquefaction, and slope failure. The microzonation maps, depicting ground-motion amplification, liquefaction, and landslide potentials, can be produced if the ground motion on bedrock (input) and the site conditions are known. These maps, in combination with ground-motion hazard maps (on bedrock), can be used to develop a variety of hazard mitigation strategies such as seismic risk assessment, emergency response and preparedness, and land-use planning. However, these maps have certain limitations that result from the nature of regional mapping, data limitations, generalization, and computer modeling. These microzonations show that when strong ground shaking occurs, damage is more likely to occur, or be more severe, in the higher hazard areas. The zones shown on the hazard maps should not serve as a substitute for site-specific evaluations.

1. Introduction

Although earthquakes occur infrequently, there is a certain seismic hazard and risk in the central United States, particular in the New Madrid region where the well-known New Madrid Seismic Zone (NMSZ) is located (figure 1). Between 1811 and 1812, at least three large earthquakes, with magnitudes estimated between M7.0 and M8.0, occurred during a 3-month period in NMSZ (Nuttli 1973). The paleoseismic studies suggest that these large earthquakes occurred at least three times in the past few thousands of years with an average recurrence time of about 500 to 1,000 years (Tuttle *et al* 2002; Holbrook *et al* 2006). As also shown in figure 1, the Mississippi River runs through NMSZ and many communities are located on the river plain. Therefore, the site related seismic hazards are of significant concern to the central United States.

Three phenomena (hazards) can be induced at a site by strong ground shaking during an earthquake:

- amplification of ground shaking by a “soft” soil column;
- liquefaction of water-saturated sand, silt, or gravel, creating areas of “quicksand”;
- and landslides, including rock falls and rock slides, triggered by shaking, even on relatively gentle slopes.

For example, amplified ground motion by near-surface soft soils resulted in great damage in Mexico City during the 1985 Mexico earthquake (Seed *et al* 1988). Severe damage in the Marina District of San Francisco was also caused by amplified ground motion and liquefaction during the 1989 Loma Prieta earthquake (Holzer 1994). And damages in Maysville, Ky, were caused by ground-motion amplification by the near-surface soft soils

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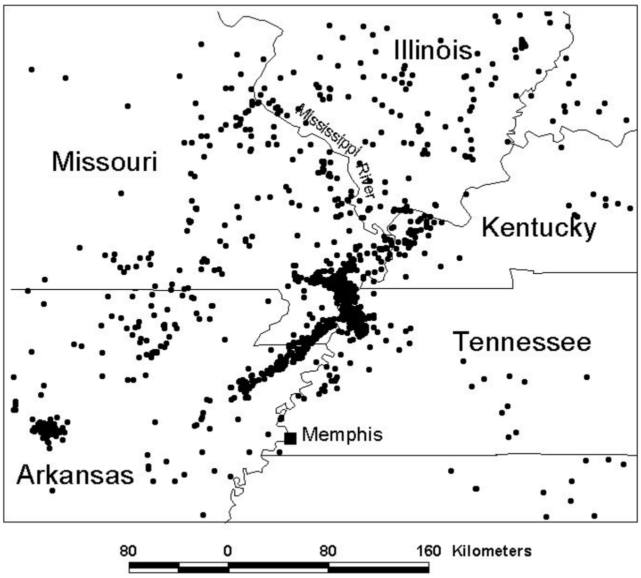

Figure 1. Earthquakes ($m_{b,\ L_g} > 2.0$) in the central United States between 1974 and 2007 (CERI 2007).

during the Sharpsburg earthquake (Hanson *et al* 1980). Seismic Microzonation is an effort to evaluate and map these hazards (i.e., amplification, liquefaction, induced landslides).

Different methodologies have been applied to characterize and map amplification, liquefaction, and landslide hazards at different scales in the central United States (Harris *et al* 1994; Street *et al* 1997, 2001; Bauer *et al* 2001; Broughton *et al* 2001; Rix and Romero-Hudock 2001; Cramer *et al* 2004, 2006). The purpose of this paper is to review the methodologies and limitations of these seismic microzonations carried out in the central United States. This will benefit similar future efforts on seismic microzonations in India and other countries.

2. Methodology

Intensity of ground motion amplification, liquefaction, and landslide is not only determined by the site conditions such as type, thickness, and shear-wave velocity of soil, topography, and hydrology, but also by the incoming (input) ground motion on rock. In other words, ground motion amplification, liquefaction, and landslide are the secondary hazards that are induced (or triggered) by the input ground motion (primary) at a site. Therefore, the primary hazard, ground motion on rock, is always assessed first. For example, the U.S. national seismic hazard maps (Frankel *et al* 1997, 2002) or ground motion hazard maps (Street *et al* 1996) depict the primary seismic hazards: ground motions on rock based on the earthquake sources and ground-motion attenuation relationships (path effects). The primary seismic hazard maps are the basis for seismic-hazard mitigations, such as building codes and insurance premiums, in a region or nation. For example, the U.S. national seismic hazard maps (Frankel *et al* 1997, 2002) were the basis for the national building and other codes (BSSC 1998). These primary seismic hazard maps are also the basis (input ground motion) for assessing the secondary seismic hazards in the central United States (Street *et al* 1997, 2001; Bauer *et al* 2001; Broughton *et al* 2001; Rix and Romero-Hudock 2001; Cramer *et al* 2004, 2006).

The types of secondary hazards present at a site or in a particular area vary with the spatial distribution of geologic materials and other factors such as topography and hydrologic conditions. For ground-motion amplification and liquefaction hazards, the physical characteristics, spatial distribution, and thickness of the soft soils are of primary concern. For analysis of earthquake-induced landslide hazard, slope may well be the most important factor, but bedrock and the physical properties of the soils overlying bedrock are both significant in any dynamic slope-stability analysis. Therefore, the soil and rock properties are the basis for microzonation. Depending on the purpose and scale of the project, the soil and rock properties can be characterized by different methods. For example, seismic reflection/refraction methods are commonly used for a regional site-amplification hazard assessment (Street *et al* 1997, 2001), whereas geotechnical investigation is needed for amplification and liquefaction hazard assessments in an urban area (Gomberg *et al* 2003). Although landslide potential hazards exist in some locations, there is no effort to map such potential in urban areas in the central United States. The methodologies used for amplification and liquefaction microzonations in the central United States are described in detail below.

2.1 *Amplification*

The physical properties, spatial distribution, and thickness and shear-wave velocity of geologic materials above bedrock can influence the strength of shaking by increasing or decreasing it or by changing the frequency of shaking. Three methods have been used to assess amplification hazard in the central United States.

2.1.1 *Empirical method – NEHRP soil classification*

The NEHRP soil classification was developed from observation and theoretical analysis in the western United States, California in particular (Borcherdt 1994). This method was adopted by the Building Seismic Safety Council (BSSC 1998) in the NEHRP

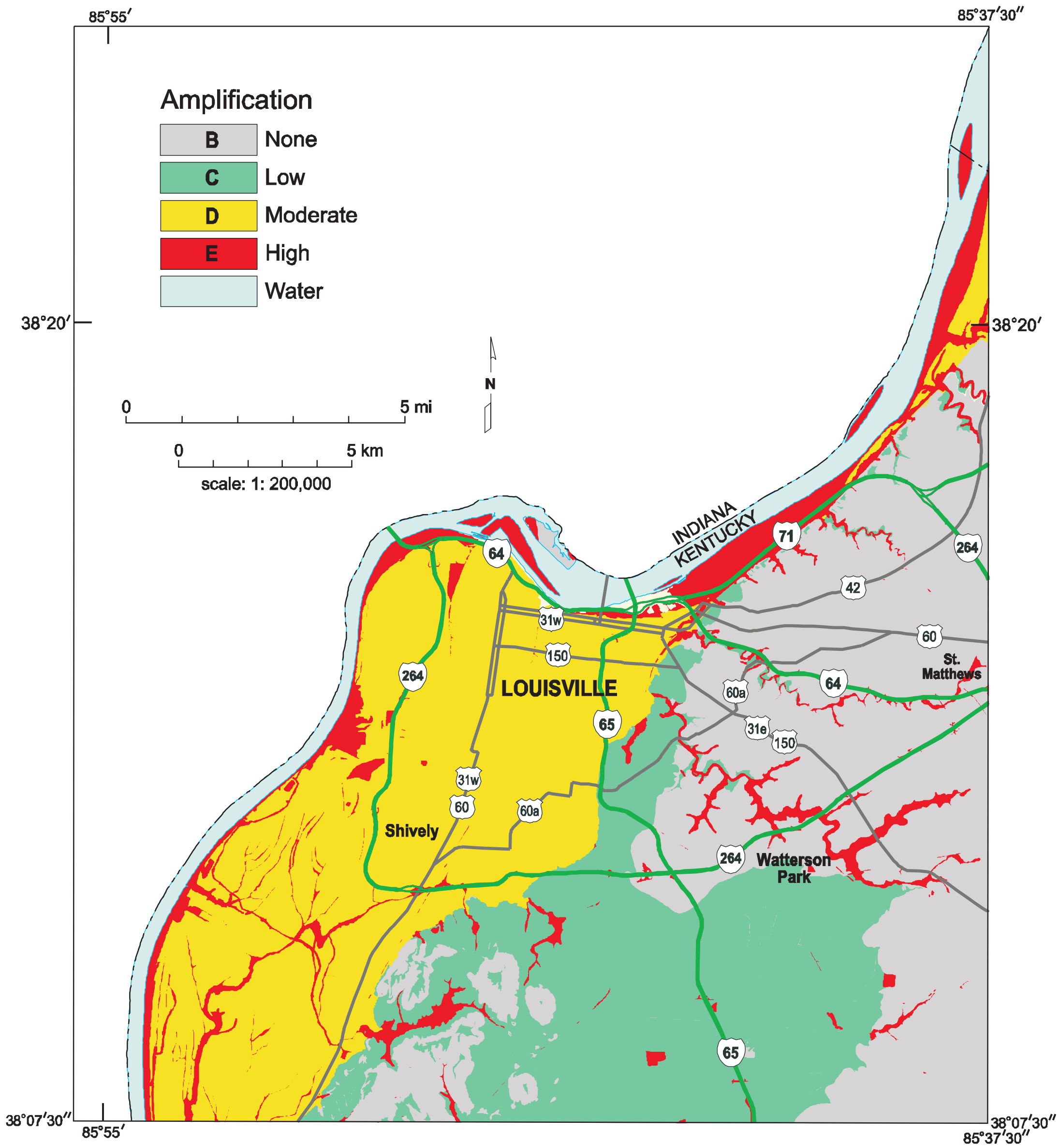

Figure 2. Amplification potential hazard in Louisville, Kentucky.

recommended provisions for seismic regulations, called the NEHRP methodology. The NEHRP methodology defines six soil categories that are based on the average shear-wave velocity, standard penetration test (SPT) value, or undrained shear strength in the top 30 m (100 ft) of the soil column. The six soil categories are hard rock (A), rock (B), very dense soil and soft rock (C), stiff soil (D), soft soil (E), and special soils (F). Category F soils are very soft soils that require site-specific evaluation. Ground-motion amplification ranges from none (hard rock/A), to high (soft soil/E and F). Street *et al* (1997) applied the NEHRP soil classification to map the amplification potential for the Jackson Purchase Region in western Kentucky based on shear-wave velocity data. This methodology was applied to map the amplification potential in the Louisville metropolitan area, Ky (figure 1). The advantage of the NEHRP soil classification is that the input ground motion does not need. The dependency on the input ground motion is tabulated based on intensity of the input ground motion and soil classification (Borcherdt 1994).

2.1.2 *1-D ground response analysis*

As described by Kramer (1996), soil response to the strong ground motion can be approximated by the transfer function of layered and damped soil on elastic rock. The fundamental frequency of the soil is:

$$f_0 = \frac{v_s}{4H}, \tag{1}$$

or the characteristic site period is

$$T_0 = \frac{4H}{\nu_s}, \tag{2}$$

where ν_s is the shear-wave velocity, and H is the thickness of soil. A computer code, SHAKE (Schnabel *et al* 1972), was written and used to perform ground response analysis. SHAKE was modified and became SHAKE91 (Idriss and Sun 1992) with an equivalent linear approach for the nonlinear response. Street *et al* (1997, 2001) applied SHAKE91 to characterize the amplification factors and associated characteristic site periods in the New Madrid Seismic Zone of the central United States. SHAKE91 was also used to map ground-motion hazards in the Memphis, Tenn., metropolitan area from scenario earthquakes in the New Madrid Seismic Zone (Cramer *et al* 2004, 2006).

The advantage of 1-D ground response analysis is that it considers full dynamic characteristics of seismic wave propagation, but it requires a time history of the input ground motion. The input time history is determined from the primary seismic hazard mapping. The drawback is that two dynamic parameters, i.e., amplification factor and site period, need to be mapped simultaneously.

2.1.3 *Site-specific probabilistic seismic hazard analysis*

This method is an extension of probabilistic seismic hazard analysis (PSHA) to include site amplification directly in the ground-motion attenuation relationship (Cramer 2003). According to Cornell (1968, 1971) and McGuire (2004), the basic formulation for hazard calculation in PSHA is:

$$\gamma(y) = \sum v \iint \left\{ 1 - \int_0^y \frac{1}{\sqrt{2\pi}\sigma_{\ln y}} \times \exp\left[-\frac{(\ln y - \ln y_{mr})^2}{2\sigma_{\ln y}^2} \right] d(\ln y) \right\} \times f_M(m) f_R(r) dm dr, \tag{3}$$

where ν is the activity rate, $f_M(m)$ and $f_R(r)$ are the probability density function (PDF) for an earthquake of magnitude M and epicentral or focal distance R, respectively, and y_{mr} and $\sigma_{\ln y}$ are the median and standard deviation at m and r. y_{mr} and $\sigma_{\ln y}$ are determined by the ground-motion attenuation relationship (Campbell 1981; Joyner and Boore 1981; Atkinson and Boore 2006). Generally, equation (3) is applied to the attenuation relationship on rock (Frankel *et al* 1997, 2002). Cramer (2003) applied the attenuation relationship on soil to calculate ground-motion hazard. This method was applied to map the probabilistic seismic hazard (including site-effect) in Memphis, Tennessee (Cramer *et al* 2004, 2006).

Recent studies (Anderson and Brune, 1999; Wang *et al* 2003, 2005; Wang 2005, 2006, 2007; Wang and Ormsbee 2005; Wang and Zhou 2007) showed that equation (3), the heart of PSHA, is invalid because it is based on earthquake science from the 1970s (point source), not on modern earthquake science. As shown in equation (3), $f_R(r)$ is introduced to account for the probability that earthquake (a single point) could occur at any point on a fault. In other words, equation (3) is based on the single point source model for earthquake. Earthquakes that are of safety concern cannot be treated as a single point. For example, the Sumatra earthquake of December 26, 2004, had about a 1200 km rupture length. The fault will break during an earthquake, and the ground motion at a site will result from a dynamic (physical) process, but not a probabilistic aggregation. Calculated hazard from PSHA does not have a clear physical meaning (NRC 1988; Wang 2005). Therefore, this method is not appropriate for seismic microzonation.

2.2 *Liquefaction*

Youd and Perkins (1978) found that the liquefaction potential of soils is related to age and depositional environment. Table 1 summarizes the liquefaction potential for several continental deposits (Youd and Perkins 1978). The first step in quantifying liquefaction hazard potential is to map the age and depositional environment of the soils. For example, Broughton *et al* (2001) mapped the liquefaction potential hazard, based on table 1 and detailed field investigations of the geologic units in Memphis, Tennessee. For those soils that have moderate to high potential for liquefaction, a further evaluation can be performed based on *in situ* tests such as the standard penetration test (SPT), cone penetration test (CPT), and shear-wave velocity (Kramer 1996).

2.2.1 *Cyclic stress approach*

According to Seed and Idriss (1971), the uniform cyclic shear stress caused by an earthquake

Table 1. *Estimated susceptibility of continental deposits to liquefaction (modified from Youd and Perkins 1978).*

	Likelihood that Cohesionless Sediments, When Saturated, Would Be Susceptible to Liquefaction (by Age of Deposit)			
Type of deposit	< 500 yr	Holocene	Pleistocene	Pre-Pleistocene
River channel	Very high	High	Low	Very low
Flood plain	High	Moderate	Low	Very low
Alluvial fan and plain	Moderate	Low	Low	Very low
Lacustrine and playa	High	Moderate	Low	Very low
Colluvium	High	Moderate	Low	Very low
Talus	Low	Low	Very low	Very low
Tuff	Low	Low	Very low	Very low
Residual soils	Low	Low	Very low	Very low

(earthquake loading) can be approximated,

$$\tau_{\text{cyc, }E} = 0.65\frac{a_{\max}}{g}\sigma_v r_d, \tag{4}$$

where $a_{\max}$ is the peak ground-surface acceleration, g is the acceleration of gravity, and σ_ν is the total vertical stress, and r_d is a stress reduction factor. The cyclic shear stress required to initiate liquefaction (liquefaction resistance) is:

$$\tau_{\text{cyc, }L} = CSR_L\sigma'_v, \tag{5}$$

where CSR_L is the cyclic stress ratio required to initiate liquefaction, σ'_ν is the initial effective stress. CSR_L is determined from *in situ* tests such as the standard penetration test (SPT), cone penetration test (CPT), and shear-wave velocity (Kramer 1996). Liquefaction will occur if earthquake loading is greater than liquefaction resistance or the factor of safety,

$$FS_L = \frac{\tau_{\text{cyc, }L}}{\tau_{\text{cyc, }E}} < 1.0. \tag{6}$$

Iwasaki *et al* (1978; 1982) derived a liquefaction potential index (LPI) based on the cyclic stress approach and used LPI to map liquefaction potential hazard in an area. Rix and Romero-Hudock (2001) used LPI that was derived from cyclic stress analyses to map the liquefaction potential hazard in Memphis/Shelby County, Tenn. (earthquake.usgs.gov/regional/ceus/products/).

2.2.2 *Shear-wave approach*

Andrus and Stokoe (1997) and Andrus *et al* (1999) found a correlation between shear-wave velocity of soil and its liquefaction potential. According to Andrus *et al* (1999), cyclic resistance ratio (CRR) is

$$CRR = \left\{a\left[\frac{V_{s1}}{100}\right]^2 + b\left[\frac{1}{V^*_{s1} - V_{s1}} - \frac{1}{V^*_{s1}}\right]\right\}MSF, \tag{7}$$

where

$$V_{s1} = V_s\left[\frac{P_a}{\sigma'_\nu}\right]^{0.25}, \tag{8}$$

a and b are constants, V_s is shear-wave velocity, P_a is a reference stress ($\sim$100 kPa), V^*_{s1} is the limiting upper value of V_{s1}, MSF is magnitude scaling factor. Liquefaction is predicted to occur when $FS = CRR/CSR_L$ is less than 1 (Andrus *et al* 1999). This approach was applied to map liquefaction potential in Louisville, Ky.

Table 2 lists the properties of geological units and bedrock derived from the surficial geologic mapping, SH-wave velocity measurements, geotechnical subsurface investigations, and water well data. According to Youd and Perkins (1978) (table 1), only the Holocene alluvium may have liquefaction potential. A further evaluation was performed for the Holocene alluvium based on the shear-wave approach. A maximum peak ground-surface acceleration ($a_{\max}$) of 0.1 g PGA, which result from an M7.7 earthquake in the New Madrid Seismic Zone (Street *et al* 1996), was used in cyclic resistance ratio. Figure 3 shows the liquefaction potential hazard in Louisville, Ky.

3. Discussion

In the central United States, many communities, such as Memphis, Tennessee and Paducah,

Table 2. *Geologic units and their average shear wave velocities in Louisville, Kentucky.*

Age	Geologic unit	Average shear-wave velocity (m/s)	Average thickness (m)	Liquefaction susceptibility	Equivalent units
Holocene	Channel and floodplain alluvium	100–200	5–20	Moderate	Qal
Pleistocene	Lacustrine deposits	160–275	3–5	None	Qla
Pleistocene	Glacial outwash	250–600	5–25	None	Qo
Pleistocene	Loess and Eolian sand	(170–300)	(3–5)	None	Ql
Pleistocene	Terrace deposits	(170–300)	(3–5)	None	Qt
	Bedrock	> 820	–	None	–

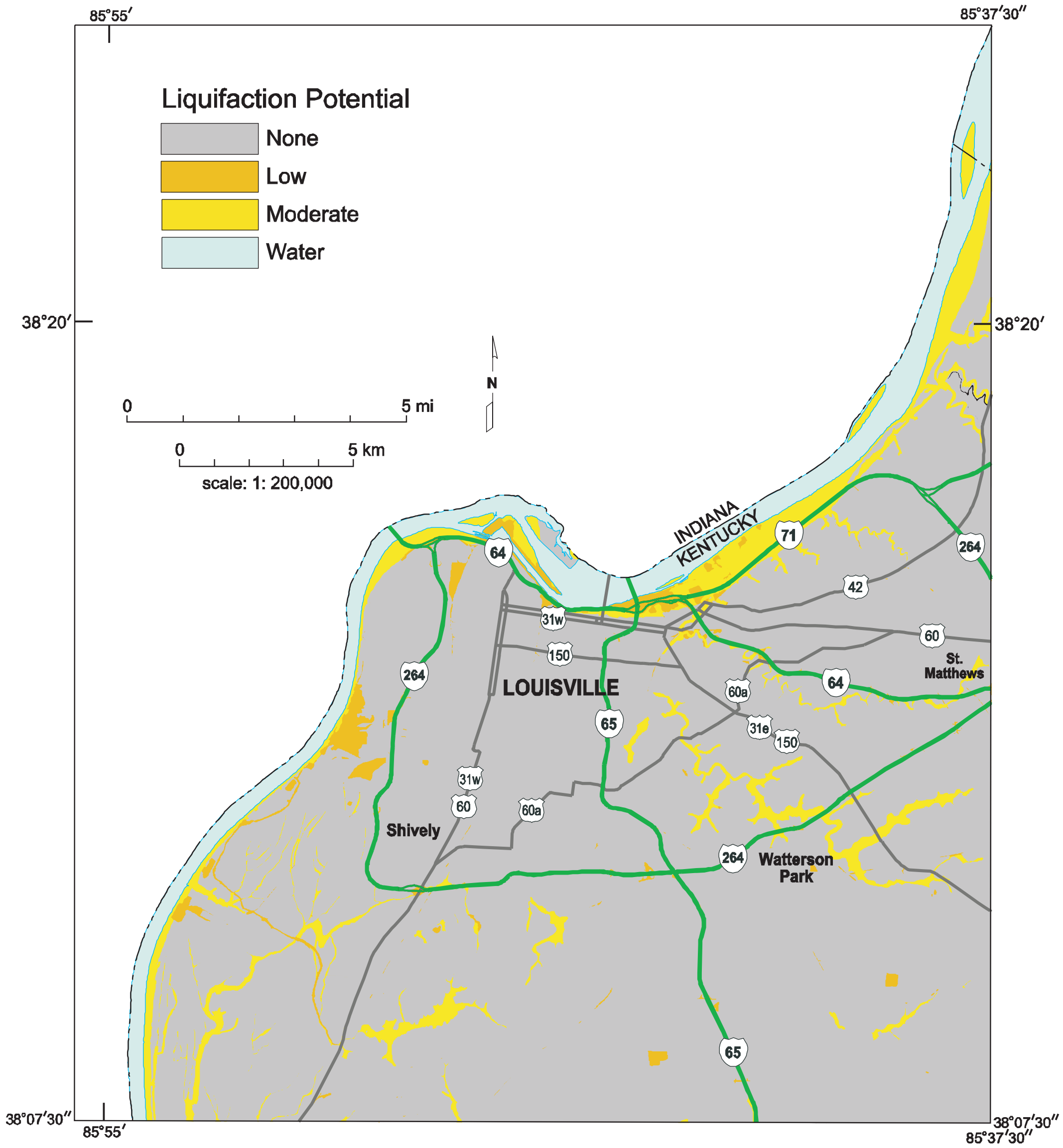

Figure 3. Liquefaction potential hazard in Louisville, Kentucky.

Kentucky, are built on soft fluviul deposits along the Mississippi and Ohio rivers. These communities could suffer additional damage due to site effects if large earthquakes, similar to the 1811–1812 New Madrid events (Nuttli 1973), occur. Efforts to characterize these effects by local geology, topography, hydrology, and other factors have been carried out in the central United States by federal, state, and local government agencies and private organizations (Harris *et al* 1994; Street *et al* 1997, 2001; Bauer *et al* 2001; Broughton *et al* 2001; Rix and Romero-Hudock 2001; Cramer *et al* 2004, 2006). Different types and scales of hazard maps have been produced based on different methodologies and site-specific data. In combination with ground-motion hazard maps (on bedrock), these seismic microzonations can be used to develop a variety of hazard mitigation strategies, such as land-use planning, emergency planning and preparedness, lifeline planning. However, there are limitations on these maps.

The zones shown on the hazard maps should not serve as a substitute for site-specific evaluations based on subsurface information gathered at a site. The calculated values of the individual map may, however, be used to good purpose in the absence of such site-specific information; for instance, at the feasibility-study or preliminary-design stage. In most cases, the quantitative values calculated for these maps would be superior to a qualitative estimate based solely on lithology or nonsite-specific information. For example, the soil classification map based solely on geology by Bauer *et al* (2001) was used in a site-specific evaluation of ground motion amplification (Kochkin and Crandell 2004). This may not be appropriate (Street *et al* 2004).

It is very important to recognize the limitations of these hazard maps, which in no way include information with regard to the probability of damage. Rather, they show that when strong ground shaking occurs, damage is more likely to occur, or be more severe, in the higher hazard areas. However the higher hazard areas should not necessarily be viewed as unsafe. These limitations result from the nature of regional mapping, data limitations, and computer modeling.

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