COOPERATIVE RESEARCH IN EARTHQUAKE ENGINEERING AND HAZARDS MITIGATION: THE CENTRAL UNITED STATES AND NORTHWESTERN CHINA

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ABSTRACT

The University of Kentucky and Lanzhou Institute of Seismology in Gansu Province and other institutes of the China Earthquake Administration established a collaborative research program on earthquake science and engineering in 2004; a series of activities have been carried out since then. Three researchers from the Institute visited Kentucky and gave lectures at UK in May 2005. Four researchers from the China Earthquake Administration visited Kentucky and gave lectures at UK in September 2005. Four researchers from UK visited Lanzhou, gave lectures at the Institute, and conducted field investigations in the Lanzhou urban area and Kunlun Mountain in summer 2006. UK received one visiting scholar from LIS in 2006 and 2007, respectively. A reconnaissance field trip was made by Zhenming Wang to the Wenchuan M8.0 earthquake area in June 2008. These activities have enhanced the collaborative relationship between UK and the Institute and understanding of the challenges and issues relative to earthquake science and engineering in the central United States and western China. These activities have resulted in several presentations at professional meetings and publications in professional journals. They have also resulted in joint research proposals to seek funding, both from Chinese and U.S. sources. All these activities have yielded a practical understanding of seismic hazards mitigation in Kentucky and Gansu Province.

1. INTRODUCTION

Selecting a level of ground motion for policy consideration, such as for building and bridge seismic design, is complicated. It not only depends on earthquake science and engineering, but also on social, economic, and other issues. Earthquake science and engineering are the basis, however.

California has the best code provisions for seismic design of buildings, bridges, and other structures in the world. The California code provisions, such as the 1997 Uniform Building Code and the seismic design methodology for bridges in California, are based on good earthquake science and engineering. As a result, the California code provisions have been used as a model for other parts of the United States and the world. The 2000 International Building and Residential Codes and later versions, which were based on the California code provisions (i.e., the Uniform Building Code), have been recommended for other parts of the United States, including the central United States (BSSC, 1998, 2004; MCEER/ATC, 2003). The California code provisions have also been used as models in China (Hu and Gao, 2004).

Although the principles of earthquake science and engineering can be applied to any other area in the world, there are some fundamental differences among regions. Differences in earthquake science and engineering between California and the central United States include the seismological and geological settings (i.e., interplate in California versus intraplate in the central United States) and a lack of observations in the central United States. Also, the deformation rate is more than 20mm per year along the San Andreas Fault in California, but less than 2mm per year along the New Madrid Fault in the central United States (Calais and others, 2006). Damaging earthquakes (M6.0 or greater) occur about every decade in California, whereas no damaging earthquake (M6.0 or greater) has occurred in the central United States since 1895 (Bakun and Hopper, 2004). The soils and bedrock underneath California are also quite different from those in the central United States: California generally has thinner soil and softer bedrock, whereas the central United States has thicker soil and harder bedrock.

These differences make it difficult to simply apply the California code provisions and engineering practices to the central United States. This is demonstrated by the difficulty in selecting design ground motion in many communities in the central United States, such as Memphis, Tenn., and Paducah, Ky. Although the ground motion with 2 percent probability of exceedance (PE) in 50 years (i.e., the ground motion with a 2,500-year return period) was recommended for seismic design of buildings, bridges, and other facilities in the central United States (BSSC, 1998, 2004; MCEER/ATC, 2003), the ground motions with 5 and 10 percent PE in 50 years (i.e., the ground motions with 500- and 1,000-year return periods) have been selected or recommended by local communities for seismic design of buildings, bridges, and other facilities. For example, the city of Memphis and Shelby County, Tenn., have selected the ground motion with 10 percent PE in 50 years for building seismic design (the 2005 Building Code of the 2005 Technical Codes for Memphis and Shelby County, Tenn.). The Commonwealth of Kentucky has selected the ground motion with 5 percent PE in 50 years for seismic design of residential buildings in western Kentucky. The Federal Highway Administration has selected the ground motion with 5 percent PE in 50 years for seismic safety consideration when retrofitting highway structures (FHWA, 2006).

Ground-motion amplification by the near-surface soft soils is another factor that needs to be considered in engineering seismic design and other policy considerations, especially for communities built on soft soils along the Mississippi and Ohio Rivers. As shown by Lin (2003), the amplified ground motion by Ohio River deposits caused severe damage (approximately $3 million) in Maysville, Ky., during the 1980 Sharpsburg earthquake (M5.2). Currently, the NEHRP soil classification (BSSC, 1998, 2004; MCEER/ATC, 2003) is used to correct site amplification in engineering design. The NEHRP soil classification was developed from observations and theoretical models in California, but the differences in geology between California and the central United States may make it inappropriate for correcting site amplification in engineering design in the central United States. Romero and Rix (2001) concluded that the NEHRP soil classes for the central United States need to be evaluated. All these factors have made it difficult for communities in the central United States to adopt the recommended seismic code provisions and engineering practices that were developed from California earthquake science and engineering.

Earthquake science and engineering are not only interdisciplinary issues, but also international issues. The knowledge and experience gained in earthquake science and engineering in the United States have been readily distributed to other countries, and the reverse is true as well. Learning from other countries is a key component of research on earthquake science and engineering in the United States. U.S. research institutions and funding agencies such as the Earthquake Engineering Research Institute, the Multidisciplinary Center for Earthquake Engineering Research, the National Science Foundation, and the Federal Emergency Management Agency have sent interdisciplinary teams to investigate major earthquakes and their consequences in other countries. The knowledge and experience learned from other countries greatly advance research in earthquake science and engineering in the United States. For example, ground-motion amplification by near-surface soft soils was not considered in earthquake geotechnical engineering until 1985, when it was learned that amplified ground motion caused great damage in Mexico City. Ground-motion amplification has become an important subject of earthquake engineering since then. To this end, the University of Kentucky established a scholarly exchange and cooperative research program with the Lanzhou Institute of Seismology and the China Earthquake Administration in 2004. This paper summarizes the activities since 2005.

2. ACTIVE FAULT CHARACTERIZATION USING THE SEISMIC METHOD

Determination of active faults is one of the key components in seismic hazard and risk assessment. It is not an easy job, however. Of the many faults in the central United States, many have been imaged using near-surface seismic methods (Woolery and others, 1993, 1996, 1999, 2003; Woolery, 2002, 2005; Woolery and Street, 2002; McBride and others, 2003). The imaging results indicate that faults outside the central New Madrid Seismic Zone have not been active since the late Pleistocene (i.e., no Holocene movement). For example, Figure 1 is a high-resolution SH-wave profile acquired along the western boundary of the Fluorspar Area Fault Complex in western Kentucky (Woolery and others, 2003). The profile shows a well-defined horst-graben structure with a complex episodic history. The high-resolution SH-wave image shows deformation extending into the Quaternary overburden, but does not show fault movement displacing Holocene horizons. This correlates with the observed low deformation rate

(<1.0mm/yr) in the intraplate region. GPS observations in the region also show that surface deformation is minimal (Calais and others, 2006).

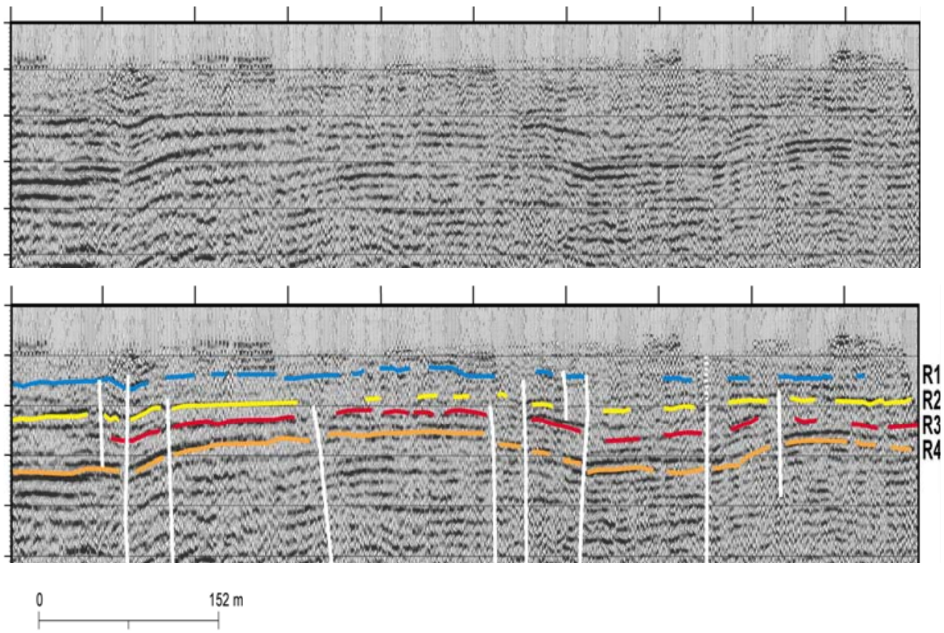

Figure 1. An SH-wave seismic reflection profile acquired in the Fluorspar Area Fault Complex in western Kentucky (Woolery and others, 2003). (top) Uninterpreted. (bottom) Interpreted. Reflector R4 (~325ms) is the top of bedrock.

As shown in Figure 2, there are many active faults in and around Lanzhou. Characterizing faults such as these in an urban environment is difficult. UK researchers have been invited by the Lanzhou Institute to participate in the Active Fault Detection and Seismic Hazard and Risk Assessment in Lanzhou project. In summer 2005 and 2006, UK researchers presented lectures and workshops on detecting and characterizing active faults using near-surface seismic methods to staff at the Institute. UK also hosted a visiting scholar from the Institute in 2007 who studied seismic data processing and interpretation. Figure 3 is an SH-wave reflection profile across the Jinchenghuan Fault in Lanzhou (Lu and others, 2007).

3. SITE EFFECTS

In the central United States, the thick Mississippi Embayment soil/sediment deposits are expected to produce significant site effects on ground motion. The site correction factor currently being used, the NEHRP soil classification (BSSC, 1998, 2004; MCEER/ATC, 2003), is based on California data, even though it is well known that near-surface soils in the central United States are significantly different from those in California. For example, shear-wave velocity for a typical bedrock in California is between 700 and 1,500 m/s, whereas shear-wave velocity for a typical bedrock in the central United States is more than 1,500 m/s. The use of the NEHRP soil classification in the central United States may not be appropriate because of these significant differences in site conditions. Romero and Rix (2001) concluded that the NEHRP site classes for the central United States need to be evaluated. Consequently, rigorously evaluating the soil transfer function of the near-surface soils in the central United States to constrain existing and future site-response models in the region is of great importance. Some progress has been made in evaluating site effects. For instance, soil conditions throughout the Upper Mississippi Embayment have been widely investigated (Street and others, 1997; Romero and Rix, 2001). Some progress has also been made in verifying the site effects through observation, using free-field and vertical downhole array strong-motion instrumentation in the central United States (Street and others, 1995; Wang and others, 2003a; Wang and Woolery, 2006). The best, although not perfect, source of information on site effects comes from a downhole array.

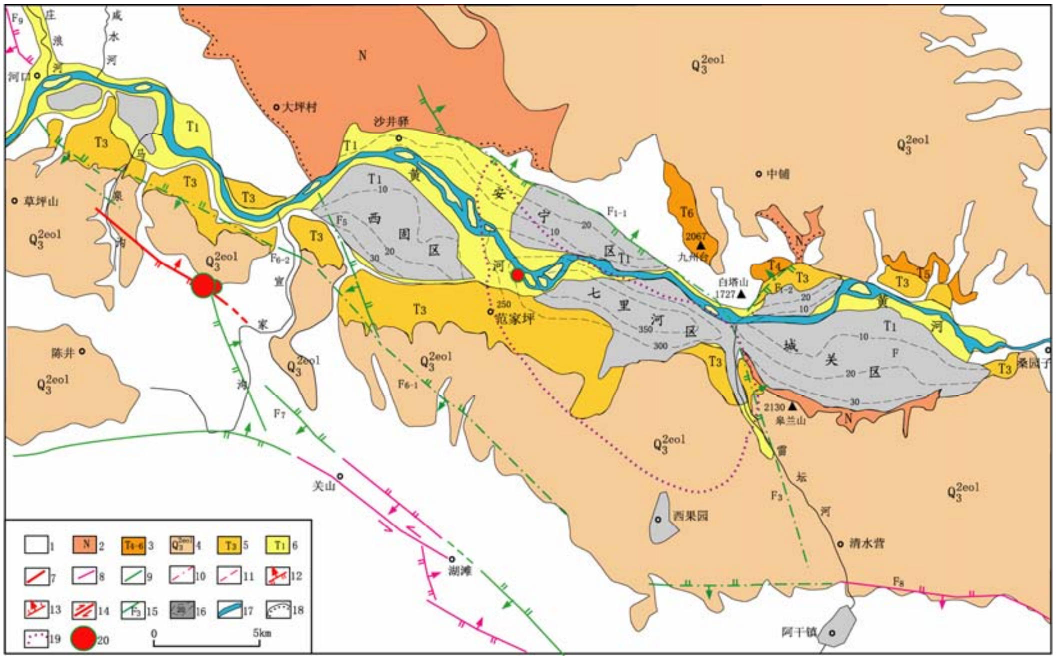

Figure 2. Active faults in the Lanzhou area.

1. Pre-Tertiary; 2. Tertiary; 3. Yellow River terraces (4-6th); 4. Loess; 5. the 3rd terrace; 6. the 1st terrace; 7. Holocene fault; 8. Late Pleistocene fault; 9. Early Quaternary fault; 10. Buried fault; 11. Projected fault; 12. Reverse fault; 13. Normal fault; 14. Strike-slip fault; 15. Fault number; 16. Urban area; 17. the Yellow Rover; 18. Unconformity; 19. Formation boundary; 20. Epicenter.

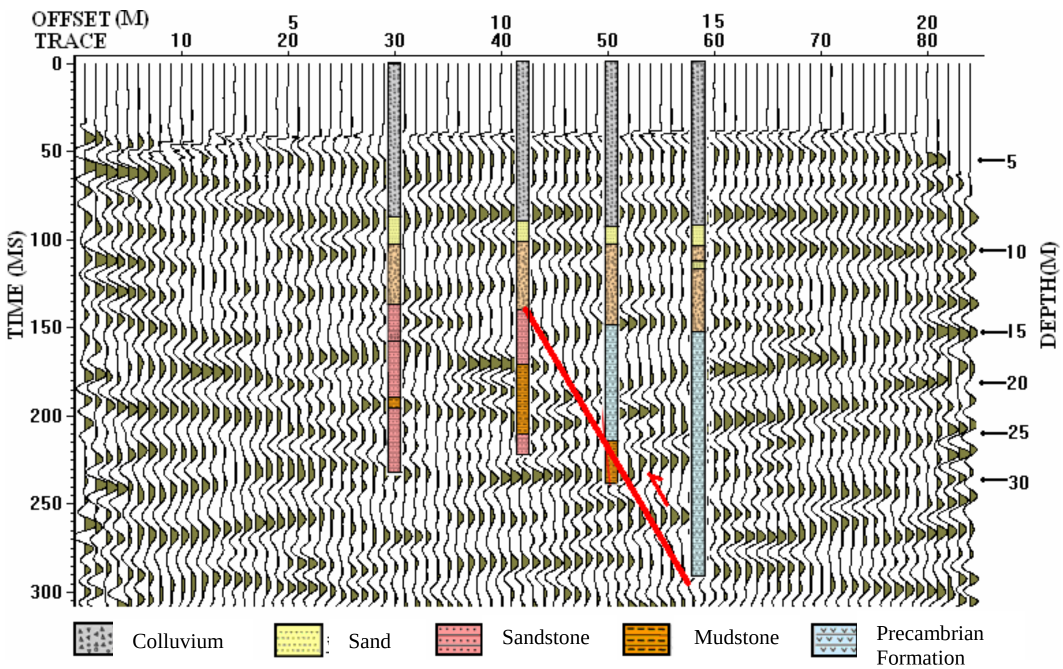

Figure 3. SH-wave reflection profile collected across the Jinchenghuan Fault in Lanzhou.

The University of Kentucky operates and maintains a unique vertical strong-motion network, the Central U.S. Seismic Observatory, in the New Madrid Seismic Zone (Wang and Woolery, 2006). The strong-motion accelerometer arrays, ranging from depths of 21m to 259 m, have been or were installed at several sites near the most active part of the New Madrid Seismic Zone, and some preliminary geophysical and geotechnical investigations have also been conducted at the sites (Street and others, 1995; Woolery and Wang, 2003). Figure 4 shows acceleration recordings from the October 21, 2004, earthquake (Md2.5) at vertical strong-motion array VSAS in the New Madrid Seismic Zone (Wang and Woolery, 2006). A 595m borehole penetrating the sediments (585m) and bedrock (10m) was completed at VSAS in late 2006.

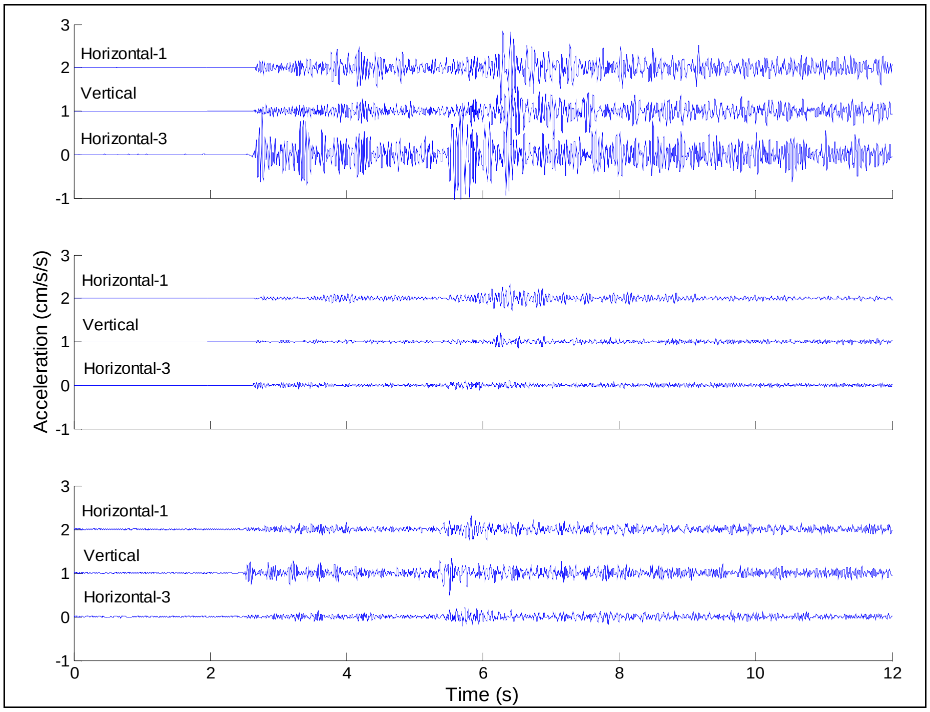

Figure 4. Acceleration recordings from the October 21, 2004, earthquake (Md2.5) at vertical strong-motion array VSAS. Top—surface, middle—30m deep, bottom—260m deep (Wang and Woolery, 2006).

As shown in Figure 2, Lanzhou is sitting on Yellow River terraces with thick sediments, particularly loess. Ground-motion amplification by the sediments could be a significant factor that must be considered in seismic design and other considerations. Table 1 lists amplification factors for loess in the Lanzhou area. As shown in the table, the amplification factor increases with the thickness of the loess; the predominant period also increases with the thickness of the loess (Wang, 2003). Studies in the central United States, however, show that the amplification factor decreases there with thickness of the sediments (Street and others, 1997; Romero and Rix, 2001). We also conducted experiments on characterizing dynamic properties of permafrost, as well as active fault characterization, using the seismic method, in the Kunlun Mountain region of the Qinghai-Tibet Plateau. Figure 5 shows an SH-wave reflection profile collected across the surface rupture of the 2001 Kunlun M8.1 earthquake near Kunlun Pass in Qinghai Province, China (Woolery and others, 2006). The profile, the first SH-wave data in permafrost, was collected parallel to the Qinghai-Tibet Railroad (top photo in Figure 5).

Table 1. Amplification factors for loess in Lanzhou (Wang, 2003).

Deposition	Loess Thickness (m)	A_{max}/A_0	Predominant Period(s)
Alluvium (Q_4^2)	<2.0	1.03–1.22	0.15
1st terrace (Q_4^{2-1})	2–20	1.18–1.92	0.20–0.25
2nd terrace (Q_4^1)	8–20		
3rd terrace (Q_3^2)	>20	1.25–2.07	0.30
4th terrace (Q_2^2)	>50	1.70–2.17	0.40
5th terrace (Q_2^1)	>250	2.74–3.04	$\geq$0.5

Note: A_0 is the input peak acceleration on bedrock;A_{max} is the peak acceleration at free-surface.

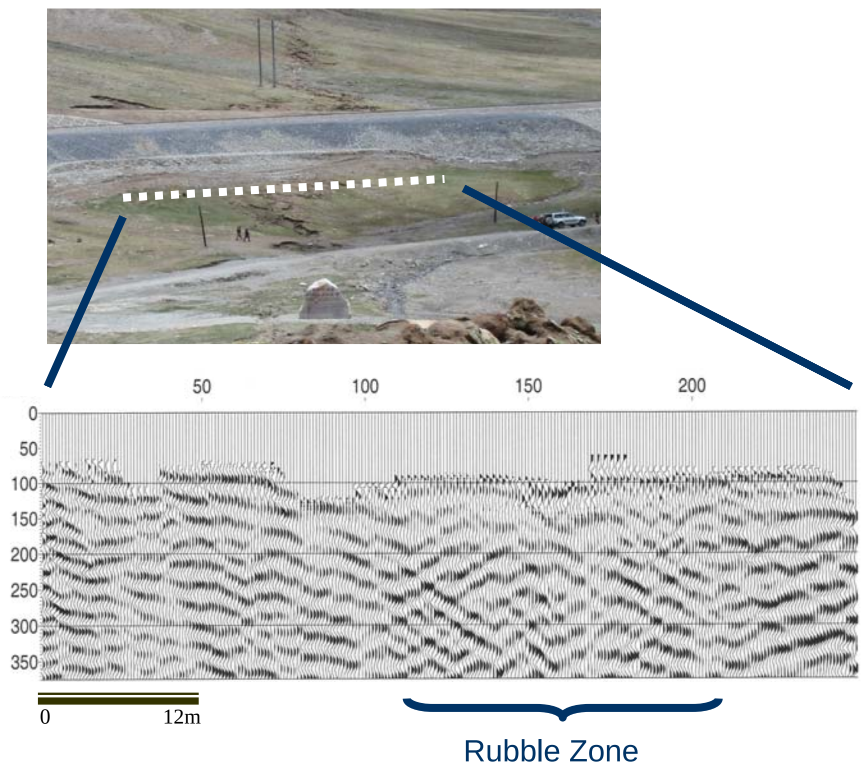

Figure 5. SH-wave reflection profile across the Kunlun Fault near Kunlun Pass.

4. SEISMIC-HAZARD ASSESSMENT

Seismic-hazard estimates can be dramatically different depending on the definitions and methods used. The same is true for seismic-risk estimates. Seismic hazard and risk are two fundamentally different concepts (Reiter, 1990; Wang and Ormsbee, 2005; Wang, 2006), but they have often been used interchangeably (Wang and others, 2005; Wang and Ormsbee, 2005; Wang, 2006). Seismic hazard is a natural phenomenon generated by earthquakes, such as a surface rupture, ground motion, ground-motion amplification, liquefaction, or induced landslide, that has the potential to cause harm, and is quantified by two parameters: a level of hazard and its recurrence interval. Seismic risk describes a probability of occurrence of a specific level of seismic hazard over a certain time (e.g., 50 or 75 years), and is quantified by three parameters: probability, a level of hazard, and exposure time. The relationship between hazard and risk is complicated. Seismic hazard occurs naturally and can be evaluated from instrumental, historical, and geological observations. Seismic risk depends not only on the hazard and exposure, but also on the model (i.e., time-independent [Poisson] or time-dependent) used to describe the occurrence of earthquakes. High seismic hazard does not necessarily mean high seismic risk, and vice versa. The differences between seismic hazard and risk are significant for policy-makers and engineers. More important, policy decisions are based more on seismic risk than seismic hazard. This can be illustrated in Table 2, which compares seismic hazard and risk between San Francisco, Calif., and Paducah, Ky.

Table 2. Seismic hazard and risk comparison between San Francisco and Paducah.

San Francisco	(1) M7.8 with ~100 years MRI* (2) MMI VII and greater with ~100 years MRI	(1) M7.8 with 39% in 50 years (2) MMI VII and greater with 39% in 50 years
Paducah	(1) M7.7 with 500–1,000 years MRI (2) MMI VII and greater with 500–1,000 years MRI	(1) M7.7 with 5–10% in 50 years (2) MMI VII and greater with 5–10% in 50 years

*MRI: mean recurrence interval

As demonstrated by Wang and others (2003b, 2005), Wang and Ormsbee (2005), and Wang (2005, 2006, 2007), one of the main reasons that communities have difficulty adopting policy for seismic-hazard mitigation is that understanding seismic hazard and risk, as defined by probabilistic seismic hazard analysis, is difficult (Frankel and others, 1996, 2002). Although PSHA is the most used method to assess seismic hazard and risk for input into various aspects of public and financial policy, PSHA has been found to be based on an invalid earthquake source model (point source), which leads to incorrect mathematical formulation (Wang, 2006, 2007; Wang and Zhou, 2007). This incorrect mathematical formulation leads to mixing temporal measurement (occurrence of an earthquake and its consequence [ground motion] at a site) with spatial measurement (ground-motion variability due to the source, path, and site effects) (Wang and others, 2003b, 2005; Wang, 2005, 2006, 2007), or the so-called ergodic assumption (Anderson and Brune, 1999). Temporal and spatial measurements are two basic and distinct characteristics of a physical event, such as an earthquake and its consequence (i.e., ground motion) at a site, and must be treated separately. Therefore, the use of PSHA in seismic hazard and risk estimates may not result in sound and safe engineering design (Wang and others, 2003b, 2005; Wang and Ormsbee, 2005).

An alternative method, seismic hazard assessment, has been developed (Wang, 2006, 2007). SHA combines the earthquake occurrence frequency (Gutenberg-Richter relationship) and ground-motion attenuation relationship directly. The Gutenberg-Richter relationship describes the relationship between the average recurrence rate *(N)* or recurrence interval *(τ)* and earthquakes with magnitudes equal to or greater than a specific size *(M):*

$$\tau = \frac{1}{N} = e^{-2.303a + 2.303bM}, \tag{1}$$

where a and b are constants. The ground-motion attenuation relationship describes a spatial relationship between a ground-motion parameter *(Y)*, magnitude of an earthquake *(M)*, and distance from the source *(R)*. Generally, the attenuation relationship follows the function form of:

$$\ln Y = f(M, R) + E, \tag{2}$$

where E is uncertainty. From equation (2), M can be expressed as a function of R, $\ln Y$, and E:

$$M = g(R, \ln Y, E)\,. \tag{3}$$

Combining equations (1) and (3) results in

$$\tau = e^{-2.303a + 2.303bg(R, \ln Y, E)}\,. \tag{4}$$

Equation (4) describes a relationship between a ground motion and its recurrence interval with a level of ground-motion uncertainty at a site of distance *R* from a seismic source. The hazard curve derived through SHA is similar to those derived through flood-frequency and wind-frequency analyses and has the same meaning (Gupta, 1989; Liu, 1991; Wang and Ormsbee, 2005; Wang, 2006, 2007). SHA is similar to the approaches developed by Milne and Davenport (1969) and Stein and others (2006). It relies on historical and geological records on earthquakes and observations. There are only about 200 years of historical records on earthquakes available for the central United States. In contrast, China has about 4,000 years of historical records on earthquakes, which provide a good database for SHA. The Wenchuan M8.0 earthquake of May 12, 2008, will also provide a valuable opportunity to check the validity of PSHA and SHA.

5. SUMMARY

The University of Kentucky has established a scholarly exchange and cooperative research program with the Lanzhou Institute of Seismology and other institutes of the China Earthquake Administration in order to learn earthquake science and engineering from each other. These activities have resulted in several presentations at professional meetings and publications in professional journals. Joint research proposals to seek funding, both from the United States and Chinese sources, have also been developed. All of these activities have yielded a practical understanding of seismic hazards mitigation in Kentucky and Gansu Province, particularly in the following areas:

1. Active fault identification and characterization using the seismic method.
2. Ground-motion site effects and soil dynamic property.
3. Seismic hazard and risk assessment and mitigation policy.

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