The Kentucky NEHRP Seismic Hazard and Design Maps Workshop

Proceedings

Compiled by Zhenming Wang

Holiday Inn North
1950 Newtown Pike
Lexington, Kentucky

November 18, 2002

Kentucky Geological Survey
James C. Cobb, State Geologist and Director
University of Kentucky, Lexington

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Front cover: Damage from the 1980 earthquake in Sharpsburg, Ky. Photo by Rick Sergeant.

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Our Mission

Our mission is to increase knowledge and understanding of the mineral, energy, and water resources, geologic hazards, and geology of Kentucky for the benefit of the Commonwealth and Nation.

Earth Resources—Our Common Wealth

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Introduction

Welcome to the Kentucky NEHRP Workshop

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Communicating the results of scientific investigations to the public is one of the most important jobs we have as scientists. Scientific research is of no benefit to society if it cannot be communicated properly to the public and to nonscientist policy-makers. Nowhere is this more important than in the area of earthquakes and the potential hazards they present. Therefore, I am pleased that this workshop on seismic hazards and design maps is being held here in Lexington. This is an important issue to us in Kentucky and to the rest of the country and world as well. The past month has shown how important it is to communicate earthquake risks to the public. In Italy, 29 people died, 26 of them children in an elementary school, from an earthquake of only 5.3 magnitude. At about the same time, an earthquake of magnitude 7.9 hit Alaska, but damage there was apparently only minor. So we can see that the information exchanged at this meeting and the concepts for portraying seismic risks on maps are timely and relevant for society.

The purpose of this workshop is to bring together scientists and engineers developing seismic hazards and design maps with users of these maps. It is vital for users to understand the science behind the maps and also important for the scientists to understand how their maps affect public policy and building. The speakers for this workshop are outstanding, and have an enormous amount of knowledge and experience. In light of the need to protect public health and safety, we all are interested in hearing from them about the methods and concepts for developing seismic hazard and design maps.

I encourage open and frank exchanges of ideas during this workshop. It is our job as scientists in the public sector and our colleagues in private practice to use our knowledge to benefit society. The seismic hazard and design maps that are presented to the public should help protect society while not overly restricting areas where strict building standards are not needed.

I wish everyone here a good workshop, and thank you for coming to Kentucky.

Introduction to the Kentucky NEHRP Workshop

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The Kentucky Geological Survey and the University of Kentucky Department of Geological Sciences have been involved in seismic research in Kentucky and the central United States for over 20 years. Our primary area of interest has been western Kentucky and the New Madrid, and more recently, Wabash Valley Seismic Zones. It is interesting to note that as our knowledge base grows, our understanding of seismic activity, probabilities, source zones, and hazard and risk in the area seems to become more complex and confusing.

Our current research is focused on western Kentucky, and the Paducah area in particular, because of the uranium enrichment plant which has been located there since the 1940's, the efforts of the U.S. Department of Energy to site a hazardous waste landfill there, and the recent announcements of the intention of the U.S. DOE and the U.S. Enrichment Corporation of plans to construct a new "centrifuge" technology enrichment plant at Paducah or a similar DOE facility near Portsmouth, Ohio. Concerns over seismic hazards at the site could have a major impact on construction costs and ultimately on site selection.

The present controversy over building code issues has implications that are much more widespread than western Kentucky, and revolve around the new International Building Code, the International Residential Code, and the related use of the seismic probability maps developed by the United States Geological Survey. Criticism of some of the seismic provisions in the codes, as well as the maps themselves, appears to be widespread. Much of this relates to the issue that predicted ground motions in the Paducah area are much higher than those in regions such as California (1.0–1.2 g PGA vs. 0.4 g PGA) that are perceived to be more seismically active. However, the problem is much broader than just the maps. Many of the concerns were expressed at the recent meeting of the National Conference of States on Building Codes and Standards held in Louisville, Kentucky, October 20–22, 2002. States and municipalities are torn between the desire to adopt the new International Building Code and the International Residential Code, and the very real technical and economic issues raised by the structural engineers and architects. The codes are also certain to have a major impact on insurance rates. KGS has been working with the Kentucky Department of Housing, Buildings and Construction and the Structural Engineer Association of Kentucky to reach a workable solution for Kentucky.

Perhaps to a great extent the problem stems from the age-old controversy between theoretical and applied science. The lack of real physical evidence to assess the temporal and spatial character of seismic sources produces a wide latitude of independent judgment in the analysis process and often hinders the most reasonable selection of design values.

Our goal with this workshop is to bring the NEHRP map developers (the U.S. Geological Survey, the Building Seismic Safety Council) and the users (engineers, seismic-safety regulators, public officials, emergency managers, and planners) together to discuss seismic hazards, risk, and design in the central U.S., especially in Kentucky. We have attempted to bring together the principal parties impacted by these decisions and get the major issues on the table in order to set forth a course of action that can bring the problem to a satisfactory conclusion.

USGS NEHRP Maps

USGS Seismic Hazard Maps For the Central United States

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The U.S. Geological Survey (USGS) produces national seismic hazard maps based on the current knowledge of earthquake sources and seismic-wave propagation. These maps represent the culmination of an extensive consensus-building process among USGS and non-USGS geoscientists, consisting of a series of regional workshops, detailed feedback from experts, and an external review panel. The USGS seismic hazard maps are the basis for the probabilistic portion of the seismic design maps used in the NEHRP Recommended Provisions, the International Building and Residential Codes (IBC and IRC), and the ASCE national design load standard.

The national seismic hazard maps are probabilistic and depict ground-motion parameters with a specified chance of being exceeded in a given time period. In contrast to deterministic seismic hazard maps, the probabilistic maps take into account how often moderate and large earthquakes are expected to occur. This probabilistic methodology assesses the hazard at each location from all known potential sources of future moderate and large earthquakes by adding the hazard curve from each source. These hazard curves describe the annual frequencies of exceeding a set of ground motions. The national seismic hazard maps are based on purely scientific inputs; there is no adjustment for engineering judgments.

The national maps use logic trees to consider a range of input source models and ground-motion attenuation relations. The maps represent the average hazard derived from these various models, not a worst-case scenario. The USGS maps are based on parameters derived from direct observations: the locations and magnitudes of instrumentally recorded and historical earthquakes, the dating and spatial extent of liquefaction from prehistoric earthquakes, and the ground motions and intensities observed from earthquakes in the region and tectonically analogous regions in the world. The USGS maps include the hazard from moment magnitude **M** 7–8 earthquakes in the New

Madrid area, **M** 6.5–7 earthquakes in the Wabash Valley area, and magnitude 5–6 earthquakes throughout the region.

We recently updated the national seismic hazard maps to incorporate new geological, geophysical, and seismological findings. For the central U.S., the 2002 update maps are very similar to those released in 1996 for 2 percent probability of exceedance in 50 years, which are the seismic hazard maps used in the probabilistic portion of the IBC and IRC design maps. The maps for 10 percent probability of exceedance in 50 years have increased substantially in the New Madrid area from the 1996 maps, because of new geological information on the recurrence and magnitude of large prehistoric earthquakes near New Madrid.

The methodologies for the 1996 and 2002 maps are basically identical. For the central U.S. there are three basic components to the hazard calculation. First, we consider the hazard from **M** 7–8 characteristic earthquakes in the New Madrid area, such as the 1811–12 earthquake sequence. Paleoliquefaction evidence indicates that such sequences of large earthquakes occur in the New Madrid area about every 500 years (see talk by E.S. Schweig at this workshop). This is shown by the large areas of liquefaction observed for earthquakes around 1450 A.D. and 900 A.D. These liquefaction areas are similar to those produced by the 1811–12 earthquakes. The magnitudes of the 1811–12 sequence were estimated from their intensities. We used a consensus range of magnitude estimates for the largest of the 1811–12 earthquakes to develop a logic tree for the magnitude of repeated large earthquakes for New Madrid. For the 2002 maps we applied a logic tree with magnitudes for characteristic earthquakes in the New Madrid area between **M**7.3 and **M**8.0, with the preferred value of **M**7.7. The recent **M**7.7 earthquake in Bhuj, India, an area tectonically analogous to the New Madrid area, produced a similar pattern of intensities with distance as the largest earthquake in the 1811–12 sequence.

The second component of the hazard maps is derived from the instrumentally recorded and historical seismicity. We use the locations of earthquakes with m_{blg} 3–6 to calculate rates of seismicity on a grid. The gridded seismicity rates are spatially smoothed and the hazard is calculated from each grid cell. The seismicity grid includes the 1980 m_b 5.1 Sharpsburg, Kentucky, earthquake. It is important to note that extrapolating the rate of small earthquakes in the New Madrid area will underpredict the observed rate of **M** 7–8 earthquakes for New Madrid. This is why the **M** 7–8 earthquakes at New Madrid are described as "characteristic" earthquakes.

Liquefaction has also been found for prehistoric **M** 6.5–7 earthquakes in the Wabash Valley region. However, the rate of these large earthquakes is approximately predicted by extrapolating the rate of small earthquakes in the area. Thus, we account for the hazard from **M** 6.5–7 earthquakes in the Wabash Valley region by applying the seismicity-rate grids described above.

The third component of the hazard calculation is based on large background source zones. This approach quantifies seismic hazard in areas that have had little or no historic seismicity, but have the potential for moderate or large earthquakes.

We use a set of five attenuation relations that describe the median ground motions and spectral response values as a function of earthquake magnitude and distance. These relations also specify the ground-motion variability, which is used in the probabilistic hazard calculation. It is well known that an earthquake in the central and eastern U.S. (CEUS) with a given magnitude and distance from a site will produce higher ground accelerations than a western U.S. earthquake with the same magnitude and source-site distance. This is caused by the more-efficient propagation of seismic waves through the crust in the CEUS and the higher stress drop of earthquakes in the CEUS. Our hazard maps take this regional difference of ground motions into account.

Why Do We Have Earthquakes In the Central U.S.?

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In contrast to plate boundary earthquakes, the mechanics of intraplate seismicity are poorly understood. We know that, within stable continental regions, present-day seismicity is unevenly distributed and often highly localized. One such example is the ~200-km-long New Madrid Seismic Zone (NMSZ) in the south-central U.S., which produced three M ~7.5 events in a period of 54 days in 1811–1812. Further, paleoseismic evidence from the NMSZ suggests repeated large events every ~500 [Tuttle *et al., BSSA,* 2002] during the Holocene, yet cumulative fault offsets could be as little as ~100 meters [Hamilton and Zoback, *U.S.G.S. Prof. Pap. 1236,* 1982; Van Arsdale, *Eng. Geol.,* 2000]. Recent geodetic measurements indicate that the rate of strain accumulation is below the current detection threshold [Kerkela *et al., AGU Fall Meeting,* 1998; Newman *et al., Science,* 1999].

Based on these observations, scientists often attempt to assess hazard in the NMSZ and other intraplate regions using a conceptual framework that is appropriate for plate boundary regimes. Plate boundary faults, however, are very different from intraplate seismic zones in a number of respects. First, there is far-field relative motion across a plate-bounding fault such that interseismic velocities increase with distance from the fault to a maximum value equal to the long-term plate velocity. Over geological time, the plates on either side of the fault move past each other as rigid bodies. This means that elastic strain accumulation is geodetically observable after only a few years. Secondly, plate boundary faults cannot be considered in isolation. There are frequently multiple, discrete subparallel active faults within the plate boundary system. Further, each fault ultimately merges with other plate boundary faults such that, over geological time scales, fault-end effects are minimal and place no constraint on cumulative fault offset. Finally, motion on major plate bounding faults is geologically long-lived and continues for millions of years, with major earthquakes repeating relatively regularly throughout the lifetime of the fault.

In contrast, intraplate seismic zones are embedded within a stable, essentially rigid craton. There is no far-field relative motion across the fault. Instead, relative velocities in the far-field, in both the strike-parallel and strike-perpendicular directions, are zero. Peak displacements occur at the fault and accumulate seismically. This makes it much more difficult to assess hazard using geodetic observations. Secondly, intraplate seismic zones are generally limited in length, and cumulative displacements across the faults are thought to be small. This suggests that episodes of active seismicity are geologically short-lived. If seismic episodes continued for millions of years, cumulative offsets would be larger, and stress concentrations at the fault ends would act to lengthen the fault surface.

Given these differences, it is imperative that observations relating to intraplate seismicity are interpreted using a conceptual framework appropriate for intraplate tectonic regimes. If a conceptual framework appropriate for intraplate regimes is not used, the observational data will be ambiguous. To this end, a viable mechanical model of major earthquake generation in the NMSZ has been developed. While it may not be entirely correct, unlike the standard plate boundary models, the intraplate model presented below satisfies all first-order observations from the NMSZ.

Though the reasons are not well understood, intraplate seismic zones frequently overlie ancient failed rift zones that have been repeatedly reactivated throughout geological time. In consequence, such zones may be considered weak relative to their surroundings, thereby explaining the repeated concentration of deformation at these locations over hundreds of millions of years. Based on this premise, we hypothesize a physically reasonable, time-dependent model for the generation of repeated, intraplate earthquakes in which seismic activity is driven by localized transfer of stress from a relaxing lower crustal weak body. Relaxation of the weak zone transfers stress to the overlying crust, loading the seismogenic fault, and generating a sequence of earthquakes that continues until the weak zone fully relaxes. Given a transient perturbation to the stress field, the seismicity is also transient, but, depending on lower crust and upper mantle rheology, can have a significantly longer duration. Such a relaxation process could be triggered by any local or regional perturbations to the stress field (e.g., fluid effects, thermal effects, and/or gravitational loading due to buoyancy, topography, or other surface loads).

Theoretical finite element models demonstrate that this mechanism is indeed capable of generating a sequence of large, potentially hazardous earthquakes. For an appropriate choice of parameters, the model predicts repeating sequences of large (5–10 meter) slip events with recurrence intervals of 500 to 2,500 years and cumulative offsets on the order of 100 meters. In contrast to plate boundary regions, since the relaxing zone is finite in all directions and far-field relative velocities are zero, model-predicted surface deformation rates are extremely low, frequently much less than 5 mm/yr. In most cases, interseismic strain rates computed between damaging slip events would not be geodetically detectable, implying that the geodetic observations cannot be used to rule out the occurrence of future large earthquakes. Since the process is transient and eventually grinds to a halt (after 30–40 characteristic relaxation times), recurrence intervals generally increase with time since the initiation of the relaxation process. Note, however, that earthquake repeat times do not change significantly over time scales shorter than a few thousand years, an interval comparable to the paleoseismic record in the NMSZ. Given the limited duration of the historical seismic record, it is also nearly impossible to identify where in the relaxation process any single intraplate seismic zone might be.

Based on these findings, we can conclude that intraplate earthquakes may be generated by very different processes than those that drive seismicity at plate boundaries where two abutting plates move past one another in opposite directions. In intraplate regimes, seismicity might be a localized, transient phenomenon, and earthquake repeat times might evolve with time. Unfortunately, at this time, data limitations do not permit scientists to completely characterize and constrain the temporal evolution of seismicity in specific seismic zones. In consequences, methods used for assessing seismic hazard in the central and eastern U.S. must account for both the potentially unique behavior of intraplate seismic zones and the large uncertainties that still exist in proposed intraplate earthquake generation mechanisms.

Central U.S. Earthquake Recurrence

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In the western U.S., the delineation of faults or seismic zones and the recurrence of earthquakes on them are critical parameters for probabilistic seismic hazard assessment. Yet, for most of the U.S., and maybe much of the world, there are few if any faults exposed. In fact, faults that have broken the surface are not apparent anywhere in the central and eastern U.S. (CEUS). For that reason, the USGS National Probabilistic Seismic Hazard Maps largely use the rate and distribution of historical and instrumental earthquakes to determine the seismic hazard. In some areas, however, the geologic record of prehistoric earthquakes suggests that the rate of large earthquakes is higher than that inferred by the historical record. Three such "special zones" have been delineated for the CEUS, one being the New Madrid Seismic Zone of the Mississippi Valley. Thus far, at least, it appears that in the Wabash Valley Seismic Zone, the prehistoric rate of large earthquakes turns out to be approximately equal to that predicted from smaller earthquakes.

For the New Madrid Seismic Zone, it turns out that if the rate of small ($M \leq 5$) historical earthquakes is used to forecast to larger earthquakes the size of the three largest 1811–1812 New Madrid earthquakes (magnitude 7.5–8.0), would be expected to occur every several thousand years. Geodetic results have been interpreted as indicated return periods in the tens of thousands of years. The 1996 version of the hazard maps, however, use paleoseismological evidence to justify a return period of 1,000 years for magnitude 8 earthquakes. New studies of the record of prehistoric liquefaction suggests that repeats of 1811–1812-size earthquakes have occurred even more frequently, every 500 years on average, during the past 1,200 years. There is further evidence that the prehistoric earthquakes (in A.D. 900 and A.D. 1450) each were actually sequences of large earthquakes, similar to 1811–1812.

Kentucky Faults and Source Zones in the 2002 USGS National Seismic-Hazard Maps

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Faults

It is difficult to be certain whether or not a particular earthquake occurred on a known fault in most parts of the central and eastern U.S. (CEUS: region east of the Rocky Mountains). First, earthquake locations are uncertain, typically by hundreds of meters (yards) to kilometers (miles). Second, faults can be accurately mapped where they are exposed at the Earth's surface, but their locations become increasingly uncertain deeper in the crust. At common earthquake depths of 5 to 15 km (3 to 10 mi), fault locations are typically at least as uncertain as earthquake locations. In many cases we don't even known whether or not a fault mapped at the surface penetrates to earthquake depths. Third, most earthquakes are small and could occur on small faults. Because there are more small faults than large ones, most earthquakes might occur on faults that are too small or too deep within the Earth for us to detect.

Thousands of reported CEUS historical earthquakes demonstrate the ubiquity of seismic slip on CEUS faults. However, few CEUS faults are recognized to have ruptured the Earth's surface, presumably in an earthquake, within Quaternary time. Many CEUS geologic maps, including those of Kentucky, show mapped faults, but nearly all the faults are ancient and lack published evidence of recent slip. Each of the largest historic and prehistoric earthquakes in the central Mississippi River valley and lower Wabash River valley produced liquefaction features over a large area, but few of the earthquakes have been linked to known faults. Numerous subsurface faults are known from geophysical data, but few have been shown to offset Quaternary sediments.

For these reasons, the CEUS portion of the national hazard maps is based mainly on the locations and magnitudes of earthquakes. In the CEUS, only five faults are well enough linked to earthquakes that the faults can be used as earthquake sources in the maps. Two are in eastern Colorado and southern Oklahoma. The other three faults trend along the zigzag alignment of earthquakes just southwest of Kentucky, in the center of the New Madrid Seismic Zone. There, two northeast-trending faults are linked by a northwest-trending cross fault.

Source zones

A source zone is a region that is outlined by geologists and seismologists because its earthquakes have different abundances, sizes, or geologic controls than the earthquakes in adjacent areas. The methodology used to compute the USGS hazard maps requires only seven CEUS source zones. Five of them bear on Kentucky hazard. (1) The craton and (2) continental rim cover the entire CEUS, and their common boundary crosses eastern Kentucky and projects into western Kentucky.

(3) Within the continental rim, the Reelfoot Rift source zone encloses the New Madrid Seismic Zone southwest of Kentucky and (4) the Eastern Tennessee Seismic Zone is southeast of Kentucky. (5) Within the craton, the Tri-State Seismicity source zone encloses the locations of two very large prehistoric earthquakes in the lower Wabash Valley of Indiana and Illinois.

A.C. Johnston (University of Memphis) and colleagues conducted a worldwide survey of large earthquakes in regions that are geologically similar to North America east of the Rockies. The survey revealed that earthquakes have greater magnitudes in some geologic settings than in others. Applying this observation to the CEUS produces a boundary that runs down the western side of the Appalachian Mountains, crosses eastern Kentucky, bends westward through Mississippi, sends a projection northeastward up the Mississippi Valley and into western Kentucky, and continues southwestward across Arkansas and Texas. The boundary separates the CEUS into a central craton that has been relatively little deformed in the last billion years, and, surrounding the craton on the east and south, a continental rim of younger mountain belts and rifted areas. Historical earthquakes as large as approximately M (magnitude) 7.5 have occurred in areas worldwide that are geologically like the continental rim. In contrast, in cratons worldwide, historical earthquakes were only as large as approximately M 7.0.

The same worldwide observations that produced the craton-rim boundary require the boundary to project into eastern Kentucky from West Virginia, following the Rome Trough. The Rome Trough is an elongated, downfaulted block of the Earth's crust that is as wide as 90 km (56 mi) in Kentucky. The trough extends southwestward from the West Virginia border and dies out near the Tennessee border. In western Kentucky, the same worldwide observations require the craton-rim boundary to project eastward, from Illinois and northwestern Tennessee into western Kentucky, to follow the Rough Creek Graben, a downfaulted block of similar size and age to the Rome Trough.

Southwest of Kentucky, the Reelfoot Rift source zone contains the New Madrid Seismic Zone of Arkansas, Missouri, and Tennessee. The source zone consists of the northeastern two-thirds of the Reelfoot Rift, a downfaulted block of similar size and age to the Rome Trough and Rough Creek Graben. The elongate Reelfoot Rift source zone trends northeastward along the Mississippi River into Kentucky, includes the Jackson Purchase area, and adjoins the western end of the Rough Creek Graben. The Reelfoot Rift source zone is within the continental rim. However, the very large earthquakes and abundant smaller earthquakes of the New Madrid Seismic Zone required separate treatment of that part of the Reelfoot Rift during preparation of the national maps (http://geohazards.cr.usgs.gov/eq/index.html, and Frankel, this volume).

Southeast of Kentucky, the elongate Eastern Tennessee seismic zone is within the continental rim along the Tennessee-North Carolina border. This zone was delineated to allow separate treatment of its abundant historical earthquakes, all smaller than M 5.

S.F. Obermeier (USGS, ret.) and other paleoseismologists identified the geologic records of at least eight large, prehistoric earthquakes in and near the Wabash Valley of Indiana and Illinois, north of Kentucky. This area is in the craton, for which the worldwide survey of this and other cratons found no historical earthquakes larger than M 7. However, the two largest prehistoric earthquakes had magnitudes estimated as M 7.1 and M 7.5. This difference required a source zone to separate the locations of the two largest Wabash Valley earthquakes from the rest of the craton. Circles centered on the two prehistoric epicentral areas were joined into the oval Tri-State Seismicity source zone, within which hazard computations allowed earthquakes as large as M 7.5. The source zone extends southward a few kilometers (miles) into Kentucky.

Impact on the national seismic-hazard maps

Aside from the special treatments afforded the seismicity within the Eastern Tennessee Seismic Zone and the New Madrid Seismic Zone, the chief contribution of source zones to computation of the hazard maps was to allow specification of the magnitude M(max) of the largest earthquake presumed to be possible within each source zone. Thus, the paleoseismological results of large prehistoric earthquakes in the Wabash Valley and the observations from the worldwide survey led to specification of M(max) 7.5 within the Tri-State Seismicity source zone of the lower Wabash Valley, in the Rome Trough of eastern Kentucky, in the Rough Creek Graben of western Kentucky, in the Eastern Tennessee Seismic Zone southeast of Kentucky, and in the rest of the continental rim outside Kentucky. In contrast, M(max) was specified 7.0 elsewhere in Kentucky and in the rest of the craton outside the Tri-State source zone.

The impact of the craton, rim, and Tri-State source zones on calculated hazard in Kentucky is negligible, even though the maximum magnitude postulated for the rim and Tri-State zones, M 7.5, is much larger than the maximum postulated for the craton, M 7.0. The calculated rate of these largest presumed possible earthquakes varies from place to place according to the observed local rates of mainly small to moderate, historical earthquakes (Frankel, this volume). Historical seismicity outside the New Madrid Seismic Zone and within Kentucky is generally so sparse that these largest presumed possible earthquakes, whether of M 7.0 or of M 7.5, have very low annual probabilities. Indeed, the annual probabilities of the largest Kentucky earthquakes are so low that two other types of earthquakes dominate Kentucky hazard. First, much of the hazard comes from moderate, infrequent earthquakes of M 5–6 or, still less frequently, of M 6–7, that could occur within Kentucky. Second, additional hazard comes from strong ground motion that could propagate into the state from large earthquakes that might occur in the New Madrid and Eastern Tennessee Seismic Zones outside Kentucky.

Western Kentucky Seismicity and Neotectonics—Integrated Geophysical and Geological Solutions

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Except for the central New Madrid Seismic Zone (NMSZ) where seismicity has been linked to neotectonic structure, contemporary seismicity outside this area cannot definitively be associated with known geologic structure. This is problematic given that the seismic source zone is one of the three fundamental parameters needed to perform a seismic hazard analysis. As ground-motion modeling techniques and the associated databases of dynamic crustal properties in the central United States continue to improve, definition of potential seismogenic sources remains relatively poorly characterized. Consequently, site-specific ground-motion calculations based on source-zone boundary "judgments" are often either over- or underestimated. Therefore, the identification of discrete seismic source zones/structures (outside the central NMSZ) is a critical need to be addressed for reducing uncertainty in the overall seismic hazard assessment.

Paleoseismological, as well as historical earthquake accounts and contemporary earthquake records, indicate that the region surrounding the central NMSZ (e.g., Jackson Purchase of Kentucky, lower Wabash Valley of southern Illinois and Indiana) is exposed to seismic hazard. The pre-instrumental and instrumental evidence indicates that small to moderate earthquakes have occurred in the region; however, the lower rate of seismicity (relative to the central NMSZ) and insufficient network coverage outside of the most active part of the NMSZ make accurate correlation of seismicity and geologic structure problematic. Integrated geophysical and geologic field investigations are proving to be an efficient and cost-effective alternative of assessing potential seismogenic structure, however.

Accurate identification and characterization of near-surface geologic structures in the expansive river valleys of the seismically active central United States is often impeded by relatively thick sequences of unlithified, water-saturated sediment. The soft sediment cover conceals neotectonic bedrock structure and, apart from a few notable exceptions (i.e., Crowleys Ridge, Reelfoot Scarp, Commerce Fault, and possibly Sikeston Ridge), the sediment's inherently weak mechanical properties commonly fail to transform near-surface propagated faults and folds into significant or noticeable surface geomorphic features. Consequently, the targeting of potential neotectonic structure requires combining both traditional (e.g., well logs, geologic maps, low-resolution geophysical surveys, etc.) and nontraditional (e.g., geotechnical, s-wave birefringence) sources of information.

The University of Kentucky has utilized these sources of information to design high-resolution shear-wave (SH) seismic reflection/refraction and ground-penetrating-radar surveys to image potential near-surface tectonic deformation. These investigations have been performed in the high-seismicity areas of the central NMSZ, as well as lower-seismicity areas such as the Fluorspar Area Fault Complex and lower Wabash Valley Fault Zone. The primary objective of all surveys is to assess the timing, location, and geometry of Quaternary-aged deformation in the unconsolidated, water-saturated sediment overlying target structure. In addition, the imaged deformation zones also offer targets for paleoseismology studies to further constrain timing issues. Results, which often included subsequent drilling and carbon-14 analysis, have shown an abundance of late Pleistocene deformation, but have only recently exhibited evidence of Holocene deformation outside of the central NMSZ.

Enhancing seismic network coverage, as well as continuing these integrated field surveys, in order to reduce the uncertainty associated with seismic risk characterization, remains a priority challenge for the University of Kentucky in the United States Midcontinent.

Ground Motion Attenuation Relationships For the Central and Eastern United States

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The ground motion (attenuation) relations used in the development of the 2002 USGS national seismic hazard maps for the central and eastern United States (CEUS) are reviewed. Plots are shown that compare their attenuation and magnitude scaling characteristics for the uniform site condition (NEHRP B-C boundary or V30=760 m/sec) used to develop the maps. Additional plots are shown that compare the predicted response spectra from each of the relations. A critical decision by the USGS was the selection of the weights to use in combining the different relations. Differences in possible weighting schemes are shown to have a significant impact on the estimated ground motions, especially at near-source distances. Another important issue, unrelated to the development of the maps, but very important for engineering applications of the maps, is the selection of appropriate amplification factors to use to adjust the ground-motion predictions for the B-C boundary to other NEHRP site classes. The building code assumes that the same amplification factors can be used in both the western United States (WUS) and the CEUS, even though the underlying site conditions and shear-wave velocity profiles for a given NEHRP site class can be quite different in each region. The CEUS has relatively hard rock (of the order of 1,830 m/sec) underlying many areas, sometimes at relatively shallow depth. On the other hand, bedrock in the WUS has a shear-wave velocity that is approximately half of this value. The larger impedance can result in larger ground-motion amplification in the CEUS than in the WUS for a similar NEHRP site classification.

Assessing Earthquake Hazard and its Uncertainty in the Central and Eastern U.S.

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Infrequently occurring, major earthquakes in the central and eastern U.S. (CEUS) are certain to have significant economic and social impacts in the future. There is a need to understand the level of earthquake hazard faced by public-policy and private-sector decision makers. In assessing earthquake hazard, the first question is, what is the best method of assessment. The second question is, what level of uncertainty is involved in the assessment. As to the choice of methodology, it depends on what question about earthquake ground motion is to be addressed: deterministic methods address the impact of a single (large) earthquake, while probabilistic methods address all earthquake scenarios modeled. In the deterministic approach, the worst-case earthquake is assumed to occur, and no consideration is given to its likelihood of occurring. But ground-motion questions asking "what is the chance of" and "what is the risk/cost" are best addressed with probabilistic approaches, which account for the likelihood of earthquakes occurring. Probabilistic methods do not assume that every modeled earthquake will occur at the same time, but rather account for the probability of exceeding a ground motion given the recurrence intervals of all the earthquakes considered in the analysis. As to uncertainty, a decision (logic) tree can capture uncertainties in knowledge. Recent reassessments for both the New Madrid Seismic Zone and the southern Illinois Basin illustrate the use of a decision tree with a probabilistic assessment. A Monte Carlo (random model building) approach is used to sample the decision tree and assess both overall and individual input parameter uncertainty. The overall mean hazard estimate from an assessment that includes uncertainty agrees well with the current USGS national seismic hazard maps. The 2002 updates to the USGS national seismic hazard maps (Frankel, this workshop) show that the results from recent paleoseismic studies (Schweig, this workshop) about double the 500-year ground-motion hazard in the New Madrid region. Comparisons between deterministic and probabilistic seismic hazard maps show that deterministic estimates exceed 1.0 g in the CEUS and hence exceed probabilistic estimates.

Summary for the USGS NEHRP Hazard Maps

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In the central United States, the question is not "do we have earthquakes, seismic hazards, and risk?" but "where, how big, how often, and how strong?" Except in the New Madrid Seismic Zone, where earthquakes concentrate along the active faults, earthquakes in the central United States occur in a quite large area and do not associate with any specific zone or fault. In comparison to typical plate-boundary seismic zones such as coastal California, the central United States is located in the middle of the continent and has a totally different tectonic setting. The source mechanics are also different (Kenner, this workshop). The exact boundary of the New Madrid Seismic Zone is still difficult to define, even though it is the most active and well studied in the country (Wheeler, this workshop). The biggest historical earthquake to have occurred in the central United States was the 1811–1812 New Madrid events. The estimated magnitude ranges from about M7 to M8—a large range (Frankel, this workshop), though it has been well studied. Earthquakes are also infrequent, especially large earthquakes that have significant impacts on buildings (Cramer, this workshop). Recurrence intervals for the large earthquakes are quite long, ranging from about 500 years in the New Madrid Seismic Zone to about 4,000 years in the Wabash Valley Seismic Zone; they are even longer in other zones. These recurrence intervals were primarily determined from paleoliquefaction studies (Schweig, this workshop). Several ground-motion attenuation relationships are available for the central United States (Campbell, this workshop). However, all the attenuation relationships were developed based on numerical modeling and sparse strong-motion records from small earthquakes. These attenuation relationships have large uncertainty and predict much higher ground motions in comparison with similar-magnitude earthquakes in California.

The answers for the questions, "where, how big, how often, and how strong" are difficult ones in the central United States. The U.S. Geological Survey NEHRP seismic hazard mapping in the central United States is an effort to answer the question "what level of ground motion (seismic hazards) could be expected?" Three data sets, earthquake sources (where and how big), earthquake occurrence frequencies (how often), and ground-motion attenuation relationship (how strong) are needed for probabilistic seismic-hazard analysis (PSHA). Therefore, the answer for the question becomes much more difficult. Several well known studies on the PSHA for the central and eastern U.S., one of which was done by the Electric Power Research Institute in 1993, have concluded that there is no consensus on earthquake sources, earthquake occurrence frequencies, and ground-motion attenuation relationship. This can be seen from several presentations given at this workshop (Campbell, Cramer, Wheeler, and Woolery). Although the USGS has tried its very best to use the latest scientific information to estimate ground-motion hazards in the central United States, large uncertainties were inherited in the hazard maps. The currently available probabilistic ground-motion hazard maps were produced by the USGS with 10, 5, and 2 percent probability of being exceeded in 50 years—equivalent to 500-, 1,000-, and 2,500-year return periods—based on purely scientific inputs (Frankel, this workshop).

PSHA assesses the hazard at each location from all known potential sources of future moderate and large earthquakes by adding the hazard curve from each source (Frankel, this workshop). PSHA addresses the chance of being exceeded at a particular level of ground motion. The ground motion derived from PSHA is artificial and does not represent a real ground motion from any earthquake. The deterministic methodology (DSHA) determines ground motion from a single earthquake that has maximum impact. DSHA addresses the ground motion from a single (i.e., maximum magnitude, maximum considered, or maximum credible) earthquake (Cramer, this workshop). The ground motion derived from DSHA represents real ground motion from a single earthquake. In terms of ground motion, PSHA and DSHA are not comparable.

For PSHA in the central United States, we deal with characteristic earthquakes with long recurrence intervals and large uncertainty of the ground-motion attenuation relationship. How do these large recurrence intervals and ground-motion uncertainties affect seismic hazard estimates? A direct comparison between the USGS 1996 and 2002 hazard maps (2,500-year return period) indicates that the ground-motion level is increased in the New Madrid area on the 2002 maps even though the mean magnitude of the characteristic earthquake is decreased from 8.0 (1996) to 7.5 (2002), with increase in the mean recurrence interval from 1,000 (1996) to 500 (2002) years, and lower ground-motion attenuation relationships were included. The increase in ground motion in the New Madrid area is due to a larger uncertainty included in the 2,500-year hazard maps (Cramer, this workshop).

The mean recurrence intervals for the characteristic earthquake in the New Madrid Seismic Zone are about 500 years, and about 4,000 years for the Wabash Valley Seismic Zone. The contributions to ground-motion hazards with 500-year return period from the characteristic earthquakes in the New Madrid and Wabash Valley Seismic Zones are zero. The contributions to ground-motion hazards with 1,000-year return period from the characteristic earthquakes in the New Madrid Seismic Zone are equal to the median ground motion, but there is no contribution from the characteristic earthquakes in the Wabash Valley Seismic Zone. For the hazard with 2,500-year return period, a large contribution from the characteristic earthquakes in the New Madrid Seismic Zone is from ground-motion uncertainty. However, there is still no contribution from the characteristic earthquakes in the Wabash Valley Seismic Zone to the ground-motion hazards with 2,500-year return period. It is generally acknowledged that the hazard maps with 10 percent probability of being exceeded in 50 years are not adequate for seismic design for the central United States. This is because the hazard maps do not capture hazards from the characteristic earthquakes that are of concern. On the other hand, the hazard maps with 2,500-year return period could be too conservative in areas surrounding the New Madrid Seismic Zone, because of the large contribution from the ground-motion uncertainty (Cramer, this workshop), and still not adequate in areas surrounding the Wabash Valley Seismic Zone. These analyses show that the large and uneven uncertainties inherited in the maps make it difficult to use the hazard maps with a uniform return period for seismic-hazard mitigation and risk reduction in the central U.S. The hazard with 500-year return period does not provide enough protection against any characteristic earthquakes, such as the 1811–1812 New Madrid earthquakes, in the central U.S. However, the hazard with 2,500-year return period provides over-conservative protection against the 1811–1812 New Madrid type of earthquake in the New Madrid area, and still not enough protection against the characteristic earthquakes in other seismic zones, such as the Wabash Valley Seismic Zone.

Large background earthquakes were used in the 1996 USGS hazard maps; even larger background earthquakes were used in the 2002 USGS draft maps (Wheeler, this workshop). The background earthquakes do not make any contribution to the total hazard calculation in the central U.S. because of (1) a large area source zone and (2) a longer recurrence interval (Wheeler, this workshop). The purpose of introducing background earthquakes in PSHA is only to provide a minimum level of ground motion. If the large earthquakes are possible, they need to be reflected on the hazard maps. For example, the background earthquake of M7.5 was used for the Rough Creek Graben and Rome Trough in Kentucky, but the hazard maps do not include any contribution from the background earthquakes, for the reasons discussed. Use of the large background earthquakes in the NEHRP hazard mapping in the central United States is only to provide a minimum ground-motion hazard for areas outside active seismic zones. It is very important to note that the purpose of introducing background earthquakes in PSHA is only to provide a minimum level of ground motion. The use of large background earthquakes in PSHA has caused confusion, even among seismologists. Cramer (this workshop) used the background earthquakes to calculate median ground motion for the central U.S. that results in very high ground motion (>1.0g PGA) everywhere.

The NEHRP seismic hazard mapping is aimed at providing basic seismic-hazard information (ground-motion hazard, in this case) that can be used by the Federal, State, and local governments, as well as private organizations. The seismic hazard maps produced by the USGS for the central U.S. inherited large and uneven uncertainties that make them difficult to use for seismic-hazard mitigation and risk reduction in the region. Many, if not most, of the users are not seismological sophisticates, and thus do not have an appreciation of the role of complexity and uncertainty of geology and seismology in the probabilistic calculations for the central United States. Users (i.e., regulators, planners, etc.) often assume uniform uncertainty in the maps, and as a consequence are generally unwilling to compromise when ground motions are obviously unrealistic in some areas. A more thorough discussion of the uncertainty for this classification of users is needed, along with suggestions for alternative practical assessments when discrepancies arise. The problem, to a great extent, perhaps stems from the age-old controversy between theoretical and applied science (Kiefer, this workshop). Seismic hazard mapping is an applied science. Adjustments based on observations and engineering judgments are needed in the NEHRP seismic-hazard mapping.

NEHRP Seismic-Design Maps

Development of the Earthquake Ground Motion Maps in the NEHRP Provisions

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In the early 1990's, the Federal Emergency Management Agency (FEMA), the Building Seismic Safety Council (BSSC), and the earthquake engineering community recognized that updates of the earthquake ground maps in the NEHRP Provisions and the model building codes were needed. The existing maps were 30 years old, there was a significant increase in recorded earthquake data and scientific knowledge, and there was a need to consider the differences in the seismic hazard in the different regions of the U.S. Consideration of this increase in information and knowledge was needed in order to achieve the desired structural performance goals of the NEHRP Provisions and the model building codes. These structural performance goals are to

1. minimize the risk to occupants
2. increase the performance of higher-occupancy structures
3. improve the capability of essential structures to function, and
4. ensure a low likelihood of collapse for ground motions in excess of the design levels.

In 1994, FEMA, BSSC, and the U.S. Geological Survey (USGS) developed Project '97 to work together in developing updated earthquake ground-motion maps which could be incorporated into the 1997 NEHRP Provisions and considered by the model building codes. A Seismic Design Procedure Group, with representation from regions across the U.S., was formed to develop the maps. As a part of the project, the USGS held regional workshops across the U.S. to obtain regional expert input on the parameters and data to use in developing updated seismic hazard maps. These updated seismic maps developed by the USGS were used by the Seismic Design Procedure Group to develop the earthquake ground-motion maps for the Provisions.

The basic changes in the ground motion maps developed for the Provisions, when compared to the previous maps, are

1. maps are contour maps instead of zone maps
2. maps represent response spectral accelerations for T=0.2 and T=1.0 seconds instead of A_A and A_V
3. maps provide ground motion for the maximum considered earthquake ground motions (2 percent in 50 years) instead of design ground motions. Seismic design margin is used to obtain design ground motion values, and
4. deterministic maps are used in areas of known active faulting with defined slip rates and maximum expected earthquake magnitudes.

The maps represent a rock site condition (Site Class B), which is the same site condition as the previous maps used in the Provisions and model building codes. Soil site coefficients are used to determine the ground motions for other site conditions.

In the majority of the U.S., the changes in the design ground motion values obtained from the new and the old maps (Site Class B) are not significant and should not have any significant impacts on the design of structures. There are increases in ground motions in coastal California, Pacific Northwest, Salt Lake City, Utah area, New Madrid, Missouri, area, and Charleston, South Carolina, area. These increases result from increased knowledge and data gained in the last 30 years concerning seismicity, faulting, occurrence rates, geology, paleoseismicity, etc.

The framework established to develop the earthquake ground-motion maps can be used for making future changes that may be needed as more earthquake information and knowledge is obtained. In addition, the framework will allow for smooth transition to future performance level designs.

NEHRP Design Maps Issues

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The design earthquake specified in the NEHRP Recommended Provisions (1997 to current edition) for the design of buildings in the United States has been dramatically revised. In these editions, the maximum considered earthquake (MCE), which is corresponding to an earthquake with a 2 percent exceeding probability in 50 years (a return period of about 2,500 years), is introduced. The design ground motion is then taken as two-thirds of the MCE ground motion. It is noted that the aforementioned ground motion is for the design of ordinary buildings. The high-risk buildings and essential buildings are designed for much higher level (or longer return period) of ground motion resulting from the use of occupancy importance factors. Several issues related to the use of MCE in the seismic design of building are as follows:

1. In the United States, only one level of earthquake (e.g., MCE) is used in seismic design of buildings. However, the selection of any one level of earthquake cannot reflect the entire range of seismic hazard imposing on a city (or a county). In principle, we should not design buildings against only one level of earthquake, even though the designers prefer one-level seismic design to facilitate the design process. If we utilize the life cycle seismic design, in which the chance of earthquake occurrence is considered, we can show that the expected annual seismic risk in the eastern and central United States (ECUS) is not as severe as in California. In view of this, the selection of MCE as the basis for design earthquake in the ECUS may be conservative.
2. An appropriate way to design buildings against a large infrequent earthquake (MCE) is to provide buildings with ductility to limit structural deformation instead of increasing strength. The design approach in the NEHRP provisions is a strength-based approach. Thus, the NEHRP provisions may not be appropriate for the design of buildings against MCE.
3. It is well recognized that great uncertainties are associated with the estimation of ground motion with a long return period, particularly in the ECUS.

From the consideration of expected seismic risk, ductility versus strength to resist a large infrequent earthquake, and great uncertainties in estimating ground motion with a long return period in the ECUS, we believe that the use of MCE as the basis for the design of ordinary buildings in the ECUS is not appropriate. It will result in an increase in structural strength and it is probably costly and ineffective. As an alternative, the buildings in the ECUS should be designed for serviceability against a design earthquake with a short return period, which can be estimated with less uncertainty. Then, the buildings should be provided with sufficient ductility to resist large infrequent earthquakes.

The maps displaying ground motions in the NEHRP Provisions are basically developed by the U.S. Geological Survey (USGS). A few comments on the NEHRP design maps (USGS National Seismic hazard maps) are as follows:

1. The use of probabilistic seismic hazard analysis (PSHA) to define ground motion for the design of buildings is flawed. It is impossible to have an earthquake occurring at two distinct faults at the same time. Thus, we need to consider each fault separately in the PSHA to define ground motion for the design of buildings.
2. The so-called uniform-hazard response spectrum defined by two spectral values is fictitious. It is not corresponding to any earthquake event and it may be not appropriate for use in the performance-based earthquake engineering, which may require realistic ground motion (response spectra or time histories) resulting from an earthquake event.
3. The deaggregation analysis process to determine a dominant event (magnitude and distance) for the design of buildings is convoluted and cumbersome.
4. The design ground motion expressed in terms of spectral values corresponding to a 2 percent exceeding probability in 50 years is too difficult to understand by decision-makers and stakeholders.

In my opinion, the design earthquakes can be easily determined as follows:

1. Identify active faults (seismic sources) and establish the characteristics of each fault, such as the fault type and the recurrence relationship.
2. Display the information of active faults in an interactive online map and include the map in the commentary of a building code.
3. Determine design earthquakes (magnitude and location) for each local jurisdiction (e.g., each county) by considering the characteristics of each fault affecting each county and the consensus of acceptable risk adopted by the community in each county. It is noted that this is a decision making based on political and economic considerations as well as seismic and engineering analysis.
4. Display the design earthquakes in an interactive online map and include the map in the provisions of a building code.

It is noted that once a design earthquake (magnitude and location) is specified, all others (attenuation of ground motion, site effects, etc.) are technical issues, which can be addressed in different sections of a building code. In addition, the corresponding response spectra and even time histories can be established. This approach has been used by departments of transportation and utility companies to establish design earthquakes for the design or retrofit of highway bridges and utility facilities. This approach can also unify seismic hazard definitions used by different users, such as emergency managers and insurance companies.

Assessment of the IBC 2000/NEHRP 97 Seismic Safety Provisions

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Jurisdictions throughout the New Madrid Seismic Zone (NMSZ) are considering adopting International Building Code 2000 (IBC 2000) that addresses the earthquake hazard. It will require radical increases of structural integrity for new buildings approaching the levels used in California. The purpose of our report is to evaluate the changes in the level of safety resulting from this new code. Our estimates indicate increases of building costs by 10–35 percent without comparable benefits in public safety. Costs for seismic mitigation are excessive; therefore, we recommend an alternative and less-expensive strategy based on the fact that large earthquakes in the New Madrid Seismic Zone are far less common than in California.

Here, as elsewhere, a community's choice of building codes in earthquake-prone areas reflects a complicated interplay between safety, seismology, earthquake engineering, economics, and public policy. Ideally, building codes should not be too weak, permitting unsafe construction and undue risks, or too strong, imposing unneeded costs and thereby promoting evasion. Deciding where to draw this line is a complex policy issue for which there is no unique answer. Local jurisdictions are under no obligation to blindly accept national building codes, but if they do they may find it useful to modify them to best balance the local hazards and costs.

Earthquake risks are not well understood in the NMSZ. Earthquake risk assessment has been described by one of its founders as "a game of chance of which we still do not know all the rules." Nowhere is this more the case than in the Memphis area and the remainder of the New Madrid Seismic Zone (NMSZ), where large earthquakes occurred in 1811–12 and probably earlier. However, the underlying physical cause of the earthquakes is unclear; the magnitudes and recurrence times for the largest earthquakes are difficult to infer, and the likely ground motion from such earthquakes is essentially unconstrained. The problem is that earthquakes in the New Madrid Seismic Zone are rare. On average, one potentially serious earthquake (magnitude 6) occurs every 100 years somewhere in the NMSZ, as contrasted with one every 10 years in California.

It appears that the model used to develop Geological Survey National Seismic Hazard maps associated with the IBC 2000 overestimate the hazard. In part, this stems from the assumption that ground motion from earthquakes significantly exceeds that derived from other accepted models. Adding still more exaggeration, the recurrence interval of the probability of exceedance was changed from once in 500 years to once in 2,500 years. Reaching out over an extended time frame weighs the prediction toward a high seismic hazard. This gives the impression, when historical records would indicate otherwise, that the New Madrid Seismic Zone is comparable to that of San Francisco or Los Angeles in the number of earthquakes and the intensity of predicted ground motion.

We recommend an alternative that produces a reasonable level of risk for building design. Ground motion predicted by the USGS maps should be based on an exceedance of one in 500 years. The resulting accelerations are significantly lower. The lower recurrence interval would more closely represent what has actually been recorded. This approach seems more realistic, given how rare major earthquakes are in the NMSZ. Furthermore, it provides a reasonable level of safety at a cost acceptable to the community.

Kentucky Highway Bridge Seismic Design

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The current seismic design for Kentucky is based on the AASHTO current specifications using Peak Ground Accelerations (PGA) as per AASHTO maps and supplemented by maps provided by the University of Kentucky (UK) for 10 percent in 50 years or a 500-year event. UK also furnished maps for 10 percent in 250 years (2,500-year event) and 10 percent in 500 years (5,000-year event). The lowest design PGA for Kentucky is 0.09g. Only 35 of 120 counties exceed this 0.09g. There are 15 in western Kentucky, 15 in the northeast, and 5 in the southeast.

The proposed AASHTO LRFD code is based on response spectral accelerations as provided by USGS maps, available on the Web, for a rare earthquake (MCE) of 3 percent in 75 years (2,500-year event) and for an expected earthquake of 50 percent in 75 years (150-year event). While the USGS maps are convenient, the values for the expected earthquake have been difficult to find.

The USGS maps still provide PGA values, and we used these for comparison with the maps provided by UK. The 500-year values coincide fairly well between USGS and UK. However, the 2,500-year values provided by USGS are considerably higher than those provided by UK, even compared to UK's 5,000-year event.

The result of using the USGS values and the proposed LRFD code is that most Kentucky bridges currently in areas of high seismicity will need to be designed for higher and more severe categories. In addition, the remainder of Kentucky's bridges currently designed for Category A (less than 0.09g) could require a more stringent analysis.

These issues are under advisement by the AASHTO committee and will be further discussed at the Subcommittee's June meeting in New Mexico.

The *2002 Kentucky Building Code* and the *2002 Kentucky Residential Code*

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The Commonwealth of Kentucky has enforced a state building code since 1980. In the past, the *BOCA National Building Code* has been the model code. This code, titled the *Kentucky Building Code,* uses the model code with modifications specific to the state jurisdictions and geographical issues. With the eighth edition (2002), the *Kentucky Building Code* is now based on the *2000 International Building Code*.

Also, in the history of code enforcement in this state, the *CABO One- and Two-Family Residential Code* was cited by reference in the State code. It was left up to local authorities to decide if enforcement of the residential codes would be done. Nearly all large cities enforced the residential code, but many smaller communities and rural areas did not see any enforcement. With the introduction of the *2002 Kentucky Residential Code* (based on the *2000 International Residential Code),* all residential construction is to be regulated. The state residential code attempts to address issues as they pertain to the same jurisdictional and geographical matters as the primary code.

The Structural Engineers Association of Kentucky has worked with the Kentucky Department of Housing, Buildings and Construction in the past to help establish geographical criteria (such as seismic zoning) and to offer opinions on code interpretations. The organization was asked to help with the planning of the *2002 Kentucky Building Code* by reviewing chapters in the IBC relating to structural loads, foundations, and materials design. SEAOK prepared a white paper on the "Review of the 2000 International Building Code" for the State in February of 2001. Sixty-four revisions were suggested, including county-specific tables for seismic coefficients, ground snow loads, and design frost depths. Other suggestions included clarifications and exclusions of requirements not geographically applicable for Kentucky. Most of these recommendations have been implemented in the 2002 code.

At the same time that SEAOK's work on the primary code was going on, the state homebuilders association was involved in the review of the *2002 Kentucky Residential Code*. The end result of that review had some code officials concerned that parts of the code did not adequately address structural design issues, particularly the seismic requirements for the western counties of Kentucky. SEAOK was asked by the State to look into the residential code and make recommendations for that code too. A white paper on the "Review of the 2002 Kentucky Residential Code" was presented to the state in November 2001. The residential code had already gone to press by that time, and the Kentucky Homebuilders Association voiced objections to the SEAOK recommendations. After a series of meetings and negotiations that included the State officials, local code officials, structural engineers, and homebuilders, a revised white paper was presented, outlining 143 changes to the published code, many of which were reversions back to the original IRC language. The board has approved the recommendations, but the changes are not yet available as a public document.

SEAOK has continued to assist the State in clarifying the code issues and has closely monitored the transactions of neighboring states and the continued development of national standards to advise the code officials on any new developments.

Since the adoption and implementation of the codes, numerous problems have arisen that have caused difficulties for architects, engineers, and builders. Some have already been addressed, and revisions are forthcoming. Other matters will require some effort to resolve. A few of these matters are listed below:

Design Issues with the *2002 Kentucky Building Code*

1. Wind and seismic designs favor regular box-shaped buildings. This becomes characteristically impossible for school buildings, medical facilities, churches, and well-established industrial facilities. Strict interpretation of the codes require modal analysis for seismic and wind tunnel testing for wind. The modal analysis is doable with additional fees and time, but the wind-tunnel testing requires specialized facilities that are not readily and cheaply available. This testing requires the building of models for not only the new project but also the existing building and adjacent structures. For a small classroom wing for a sprawling rural county high school complex, the cost of the engineering could nearly equal the construction costs. Seismic analysis similarly requires efforts not normally considered in a project's engineering budget.
2. The seismic provisions of the code rely heavily on the expertise of geotechnical engineers with competence in soil dynamics and liquefaction. Many such engineers are neither trained in those fields nor are there any specific guidelines from the ICC on how these procedures should be used to meet the code's expectations. The former problem results in geotechnical studies from some firms that either ignore the seismic provisions completely or provide vague and arbitrary data designed to mitigate their responsibility, but provides the structural engineer with no useful data. The latter problem results in varying interpretations of soils data from the geotechnical consultant (not the testing procedures covered by ASTM standards, but the interpretation of data).
3. A number of large cities in this state occur either in whole or in part of river floodplain geography that requires design conforming to Site Class F classification, including site-specific response investigation. This may not be too big of an issue for large commercial projects, but the code technically imposes this requirement on even the 1500SF convenience store or a pre-engineered metal building used for housing inventory or vehicles. Cities such as Owensboro and Paducah would essentially need that work done for any building other than some houses. Many such small buildings are now done without any assistance of a design professional or are built from prototype designs. When last checked, there were only two practicing firms in this state that have the resources and expertise to correctly perform a site-specific analysis.
4. Special inspections are being difficult to interpret and implement in many cases.
5. There are instances where second-party standards are being referenced for the implementation of seismic design of special equipment and facilities that in fact offer no good design procedures whatsoever. The ASME standards cited in the section on earthquake design simply state that consideration shall be given to earthquake forces in the design. The IBC/KBC code covers the matter in much more superior detail than that. By applying the citation, it would appear that the second-party standard has precedence over the code and that some

substandard procedure would be acceptable.

6. Many of the second-party standards are still based on UBC94 and other seismic procedures. The newly published ACI 350.3-01 for liquid-containing structures is based on such procedures. There are several inconsistencies that occur with respect to these standards and the new codes. These include the correct implementation of load factors for seismic forces, and the prescriptive design procedures and equations for that seismic design category.
7. Buildings and structures previously built in conformance to State earthquake code requirements no longer comply due to a shift in seismic design category designations. It has become impossible (or at least heroic) to modify existing structures for the new seismic requirements. There is a parking structure in western Kentucky that was designed to be four stories, but only two stories were originally built. It was not possible for the remaining two stories to be added after the 2002 code without major overhauling of the structural system.
8. Geotechnical and structural requirements are inflexible for buildings in Seismic Design Categories D and higher. Many small commercial structures are subject to the same rigors of major projects, including liquefaction studies and special inspections. The code official should be given more discretion on what will be required for small projects.

Design Issues with the *2002 Kentucky Residential Code*

1. As with the IBC/KBC, the code favors simple rectangular construction with perpendicular walls. Any variation from this puts the home in a category similar to those under IBC rules. Many fine new homes are artistic expressions, incorporating roof offsets, irregular floor plans, and angled walls. Then the design professional has to be called in. In many cases, however, these issues become too complex for many architects to handle on their own, necessitating a structural expert. Many homebuyers believe that design drawings that they purchase out of a mail-order catalogue will suffice to get a new home built, and in the past it did. Many such mail-order designs are too complex to muster up to the IBC requirements, and the homeowner's budget doe not adequately fund the design professional's fees. When it comes to residential consulting, the big design firms are too busy to bother with them or they know the effort that has to be made to meet the IBC requirements exceed what would be a reasonable fee for a project of that size. Consequently, new home construction in the McCracken County area has all but terminated. People who wanted to build new homes are abandoning their plans and seeking existing homes when moving into the area.
2. The restrictions on two-story masonry veneers are too severe. It should be technically possible to incorporate design provision that would allow this detail. The provision could include shear wall tables for brick veneer construction and provision for attaching such surfaces to the framing.
3. The basement wall tables need to be expanded to account for higher wall construction. Many new homes are being built with the intent of having full ceiling heights in the basements while having sufficient space between the ceiling and the first floor for all the mechanical utilities.
4. There needs to be provisions for building roofs that overhang porch areas. This is now limited in the amount of overhang. Provisions need to be addressed on how the roof deck can be braced back into shear walls so that this restriction can be overcome.

5. The ICC needs an endorsement program for special assemblies such as ICBO and the SBCCI currently do. Such assemblies as Simpson's pre-engineered shear wall panels would remedy the issues with short walls and the "rational design" provisions. Code officials are reluctant to accept these assemblies because there is no means of addressing them in the code without the intervention of a design professional. This puts unnecessary burden on the design submittal process.
6. The definition of "rational analysis" needs to be included. It should clarify what is acceptable without necessarily calling in a design professional for its implementation. The code officials are forced to interpret it in this way. Rational design could include utilization of trade software, published articles, specialized assemblies, and the use of manufacturer's design instructions. If a contractor can demonstrate that such published data meets the intent of the code, a design professional need not be involved.

New Safety Criterion for the NEHRP Recommended Provisions: Its Basis and Measures of its Impact

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The 1997 NEHRP Recommended Provisions made a significant, but not particularly obvious, change in its basic criterion for structural safety that is directly paired with the introduction of the new ground-motion hazard maps. Couching the change in terms of performance-based engineering, the fundamental performance requirement was not changed, but the performance criterion was changed. This statement is steeped in the jargon of performance concepts for the expression of engineering standards. Thus, the fundamental performance requirement is that buildings and other structures be designed and constructed to deliver acceptable safety, considering the hazard presented by earthquake ground shaking. The 1997 edition, with its new maps and the procedure to utilize values from those new maps, does not represent any change in this fundamental requirement. Performance requirements stated in this fashion are not quantitative and are subject to reinterpretation by each user and potentially with each use. Under the performance concept, quantitative criteria are required to actually implement requirements. Prior to the 1997 edition, the structural criterion in the NEHRP could be characterized as "*avoid life-threatening damage to ordinary buildings in a design earthquake ground motion, taken nominally as that ground motion having a 10 percent chance of being exceeded in a 50-year reference period.*" This was paired with criteria for improved performance in high-occupancy buildings, essential facilities, and facilities with hazardous materials, primarily through more stringent drift limits for such structures.

The 1997 edition changed this by adopting a new criterion:

> avoid structural collapse of ordinary buildings in the maximum considered earthquake ground motion, taken nominally as that ground motion having a 2% chance of being exceeded in a 50 year reference period.

The quantification of the ground-motion hazard obviously changed, and in much, but not all, of the territory mapped, the amplitude of ground motion has increased (after adjusting for the difference between old maps based upon peak ground accelerations and new maps based upon spectral response accelerations). This increase in the ground motion is offset by the decrease in the level of performance: "near collapse" is a more liberal limit state than "life safety." The purpose of the change to is avoid large loss of life, such as occurred in Soviet Armenia in the December 1988 earthquake, where a large number of multistory apartment buildings suffered total collapse. The overall change is approximately neutral when averaged over the entire area of the U.S.; however, in areas where large earthquakes are predicted to occur infrequently, such as the middle Mississippi Valley, the net change is a significant increase in demand for seismic resistance.

The selection of the 2 percent chance in 50 years was not completely arbitrary. In round numbers, this means that the mean recurrence interval (mri) of the ground motion is 2,500 years. If one examines the design basis for other structural loads, in which a load factor is applied to a nominal load with a 50-year mri (such as 1.6 times the nominal snow load), and considers the annual probability of failure, the answers by standard statistical methods will ordinarily provide predictions of the probability for structural failure on the order of one chance in 1,000 to one chance in 10,000 per year; in other words, mean recurrence intervals of 1,000 to 10,000 years for structural failure. The nature of earthquake occurrence is that the character of the hazard varies so much from location to location that it is impossible to find a load factor that could rationally be applied to a 50-year mri nominal load. It would be necessary to provide a geographical map of load factors as well as of ground-motion amplitudes.

One might infer from the preceding description that a new limit state was actually developed quantitatively, but this is not the case. Instead, existing design procedures are used unchanged, and the design ground motion, after adjustment for site amplification factors, is divided by a factor of 1.5. This approach is the implementation of a committee opinion that in a population of buildings designed according to current seismic design provisions, significant numbers of structural collapse would not occur until the ground motion exceeded the design ground motion by a factor of at least 1.5. This adjustment in the ground motion allows continued used of the response modification factor R that accounts for ductility, overstrength, damping, and other perceived values of overall structural systems.

Kentucky, like the U.S. as a whole, shows a large variation in seismic ground shaking hazard. Consider two locations: Paducah and Covington. Paducah is close to the middle Mississippi Valley Seismic Zone and the short-period spectral acceleration in rock from the maps used in NEHRP is 2.00 times gravity, whereas Covington is so far from that zone that the similar quantity is 0.19 times gravity. In other words, the mapped hazard in Paducah is over 10 times as high as in Covington, for this particular parameter. While this seems extreme, there are certainly parallels in other aspects of structural design. In California, the design snow load varies from nil to over 400 pounds per square foot, depending on location. Designing for the average makes no sense in either case. Perhaps of more interest than the spread is the change from prior codes. If one compares the change to the 1997 edition from the 1991 edition of the NEHRP Provisions for short and tall structures and for both rock and soft soil conditions, the change, expressed as a ratio of 1997 to 1991 design values for these two locations are:

Covington				
Short building	Rock site	1.01	Soft soil	2.53
Tall building	Rock site	0.71	Soft soil	1.25
Paducah				
Short building	Rock site	3.14	Soft soil	2.82
Tall building	Rock site	1.96	Soft soil	2.35

As this illustrates, the big changes in Kentucky have to do with the seismic hazard from the middle Mississippi Valley Seismic Zone. Note that where the changes for soft soils are different that those for rock, that difference is a result of other changes on site amplification introduced in the 1994 edition of the Provisions.

Summary for the NEHRP Seismic Design Maps

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The structural seismic design criterion has been changed. Prior to the 1997 edition, the criterion in the NEHRP was "*avoid life-threatening damage to ordinary buildings in a design earthquake ground motion, taken nominally as that ground motion having a 10% chance of being exceeded in a 50 year reference period*" (Harris, this workshop). The criterion in the NEHRP 1997 edition is "*avoid structural collapse of ordinary buildings in the maximum considered earthquake ground motion, taken nominally as that ground motion having a 2% chance of being exceeded in a 50 year reference period*" (Harris, this workshop). This change is dramatic for the central United States. For low-rise buildings, the design ground motion in Paducah, Kentucky, is about the same level as in Los Angeles and San Francisco, California.

The maximum considered earthquake ground motion (MCE) is defined deterministically in coastal California from maximum magnitude earthquakes, and probabilistically in the central United States with a 2 percent chance of being exceeded in 50 years (Hunt, this workshop). PSHA addresses the chance of being exceeded at a level of ground motion (Frankel, this workshop). The ground motion derived from PSHA is artificial and does not represent a real ground motion from any earthquake. The deterministic methodology (DSHA) determines the ground motion from a single earthquake that has maximum impact. DSHA addresses the ground motion from a single (i.e., maximum magnitude, maximum considered, or maximum credible) earthquake (Cramer, this workshop). The ground motion derived from DSHA represents real ground motion from a single earthquake. In terms of ground motion, PSHA and DSHA are not comparable. It is not appropriate to combine the probabilistic and deterministic ground motion into one design ground motion. Therefore, MCE itself is not consistent in defining design ground motion.

In California, it has been observed that the structures that comply with the 1997 edition of the Uniform Building Code (UBC-97) generally performed well. The seismic design map in the UBC-97 is similar to the NEHRP 1994 edition design map, which is similar to the ground motion with a 10 percent probability of being exceeded in 50 years, even though the UBC-97 probability is smaller in most cases. So, use of ground motion with a 10 percent probability of being exceeded in 50 years provides adequate seismic design in California. This unique issue for California was identified and related to the recurrence interval of the maximum magnitude earthquake (100 to 200 years). Therefore, selection of design ground motion is not arbitrary and related to the recurrence interval of the maximum magnitude earthquake in coastal California. The median ground motion of the maximum magnitude earthquake was used in the NEHRP 97 or later editions for coastal California. The return period corresponding to the median ground motion in coastal California is twice the recurrence interval of the maximum magnitude earthquake, 200 to 400 years. In the central United States, the recurrence interval of the maximum magnitude earthquakes varies greatly, from about 500 years in the New Madrid Seismic Zone, to about 4,000 years in the Wabash Valley Seismic Zone, and to even longer periods in other seismic zones. Use of ground motion with a specific return period (2,500 years) for seismic design may not be adequate for the central United States. The return period corresponding to the median ground motion of characteristic earthquakes in the New Madrid Seismic Zone is about 1,000 years. Use of ground motion with 2,500-year return period for seismic design is too conservative in areas surrounding the New Madrid Seismic Zone because large uncertainty is included. However, the ground motion with 2,500-year return period for seismic design may not be conservative in other areas, such as the Wabash Valley Seismic Zone.

One of the policy decisions made in the NEHRP 97 edition is that "the use of the maps for design provide an approximately uniform margin against collapse for ground motions in excess of the design levels in all areas." It has been observed that the seismic safety margin is about 1.5 times the design value in California. Also, it was found that ground motion with a 2 percent probability of being exceeded in 50 years is about 1.5 times the ground motion with 10 percent probability of being exceeded in 50 years in California. These calculations show that using ground motion with 10 percent probability of being exceeded in 50 years for design can achieve the collapse ground motion having 2 percent probability of being exceeded in 50 years in California. This observation in California has led to ground motion having 2 percent probability of being exceeded in 50 years being used as the collapse ground motion for the whole United States. However, ground motion with a 2 percent probability of being exceeded in 50 years is not necessarily the collapse ground motion for the central United States. The ground motion with 2 percent probability of being exceeded in 50 years in the New Madrid Seismic Zone is much higher (> 1.0 g PGA) than the estimated ground motion (~0.6 g PGA) from the 1811–1812 New Madrid events. On the other hand, the ground motion observed from the 1980 Sharpsburg earthquake is about the same as that with a 2 percent probability of being exceeded in 50 years in northeastern Kentucky. Use of ground motion having a 2 percent probability of being exceeded in 50 years for seismic design could not provide an approximately uniform margin against collapse for ground motions in excess of the design levels in the central United States.

What is the design ground motion for the central United States? In order to answer the question, the first decision that must be made is whether to use risk-based design or performance-based design. For risk-based design, it is more appropriate to use probabilistic ground motion. The NEHRP provisions before the 1997 edition were risk-based and used the probabilistic ground motion with a 10 percent probability of being exceeded in 50 years. For performance-based design, it may not be appropriate to use probabilistic ground motion. The NEHRP 1997 edition is no longer risk-based, but more performance-based (Hunt, this workshop). The design ground motion in the NEHRP 1997 edition is the maximum considered earthquake ground motion (MCE) that was defined deterministically in coastal California from maximum magnitude earthquakes. MCE in coastal California represents the "near collapse" ground motion (Harris, this workshop), and is not associated with any specific probability. A true MCE (ground motion defined deterministically from maximum magnitude earthquakes), not the ground motion with a 2 percent probability of being exceeded in 50 years, would be more appropriate in the NEHRP 1997 or later editions.

In the central U.S., seismic hazard assessment, probabilistically or deterministically, inherits a large uncertainty due to large uncertainties in seismic sources, earthquake recurrence frequencies, and ground motion attenuations. The uncertainty in seismic hazard maps needs to be thoroughly discussed in order to select appropriate design ground motion maps for the central U.S.

The Kentucky NEHRP Seismic Hazard and Design Maps Workshop

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Total Attendees: 110

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