Research, methodology, and applications of probabilistic seismic-hazard mapping of the central and eastern United States – Minutes of a workshop on June 13-14, 2000, at Saint Louis University (paper edition)

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INTRODUCTION

The U.S. Geological Survey (USGS) is updating and revising its 1996 national seismic-hazard maps for release in 2001. Part of this process is the convening of four regional workshops with earth scientists and other users of the maps. The second of these workshops was sponsored by the USGS and the Mid-America Earthquake Center, and was hosted by Saint Louis University on June 13-14, 2000.

The workshop concentrated on the central and eastern U.S. (CEUS) east of the Rocky Mountains. The tasks of the workshop were to (1) evaluate new research findings that are relevant to seismic hazard mapping, (2) discuss modifications in the inputs and methodology used in the national maps, (3) discuss concerns by engineers and other users about the scientific input to the maps and the use of the hazard maps in building codes, and (4) identify needed research in the CEUS that can improve the seismic hazard maps and reduce their uncertainties.

These minutes summarize the workshop discussions. This is not a transcript; some individual remarks and short discussions of side issues and logistics were omitted. Named speakers were sent a draft of the minutes with a request for corrections of any errors in remarks attributed to them. Nine people returned corrections, amplifications, or approvals of their remarks as reported. The rest of this document consists of the meeting agenda, discussion summaries, and a list of the 60 attendees.

AGENDA

Tuesday, June 13

9:00 a.m.: Introduction
Welcome, logistics (Herrmann, Whittington, Frankel, Wheeler)
National maps (Frankel)
Quaternary tectonic faults (Wheeler)

10:00 a.m.: Charleston seismic zone
Earthquake chronology (Talwani)
Logic tree (Cramer)

12:00 a.m.: lunch

1:00 p.m.: Sources north and west of the New Madrid seismic zone (Wheeler)

1:30 p.m.: New Madrid seismic zone
Paleoearthquake chronology (Schweig)
Historic earthquakes (Hough, Johnston)
GPS models (Gomberg)
Logic tree (Cramer)
Stress concentrators (Talwani)*

Wednesday, June 14

8:30 a.m.: Other sources
Wabash seismic zone, southern Illinois basin (Wheeler, Frankel)
Eastern Tennessee (Chapman)
Northeastern U.S. (Wheeler)
Quaternary faults in Toronto (Mohajer)*

10:30 a.m.: Engineering concerns

Design maps (Leyendecker, Hunt)
Seismic piezocone method (Mayne)*

12:00 a.m.: lunch

1:00 p.m.: Continuation of "other sources"
U.S. earthquake registry/compendium (Johnston)*
Humboldt fault zone (Wheeler, Frankel)

2:00 p.m.: Attenuation and ground motion (Campbell*, Atkinson, Frankel, Herrmann, Mueller)

3:00 p.m.: General discussion
Summary (Frankel)
CORS GPS (Prescott)*
Other

5:00 p.m.: Adjourn

*: unscheduled talks that were volunteered during the workshop

SUMMARIES OF DISCUSSIONS

Tuesday, June 13

INTRODUCTION

National maps

Art Frankel began by noting that the current (1996) USGS national seismic-hazard maps were produced about 5 years ago, after a series of regional workshops like this one. The purpose of each workshop is not to make immediate decisions on how to update or revise the 1996 maps, but to stimulate discussions on new developments, methodology, and user concerns. Discussions will feed into production of interim updated maps in early 2001. The interim maps will be distributed for further formal and informal review, with completion of the revised maps anticipated during the fall of 2001.

Frankel then reviewed the production and use of the 1996 maps, which are the basis for design maps in the 1997 NEHRP provisions. The hazard maps, documentation, data sets, and numerous derivative products including the design maps are available at **http://geohazards.cr.usgs.gov/eq/**. The hazard maps may be thought of as horizontal slices through site-specific hazard curves, which graph annual exceedance rate, plotted vertically, vs. ground motion, plotted horizontally. The hazard curves are calculated at many thousands of closely-spaced points across the country. The annual exceedance rate is chosen to correspond to a particular probability of exceedance in 50 years. The corresponding ground motion values at a given exceedance rate are plotted on the map and contoured. At each site the exceedance rate is the weighted sum of the ground motion exceedance rates from all geographically dispersed sources that can produce shaking at the site. As a weighted sum, the curves are termed "mean hazard curves." (The process of summing the exceedances of a given ground motion is not to be confused with summing ground motions at a given probability level.)

For the central and eastern U.S. (CEUS) east of the Rocky Mountain Front, the organizing principle of the 1996 maps is to calculate hazard mainly from smoothed historical seismicity. The methodology assumes that most, but not all, moderate to large earthquakes will continue to occur near previous magnitude 3-5 events, as they have been observed to do in the past. Two large background source zones provide some protection against rare damaging shocks in areas with little known historical seismicity. Five other, smaller zones allow the incorporation of local variations in seismicity rates, b-values, or maximum magnitudes. (Details of source zones are in Wheeler and Frankel, 2000, Seismological Research Letters, v. 71, no. 2, p. 273-282; a few reprints were distributed.) Within two of these smaller zones, the large, recurring earthquakes at New Madrid and Charleston, South Carolina, are treated as characteristic earthquakes.

The 1996 maps explicitly included two CEUS faults, the Meers fault in Oklahoma and the Cheraw fault in Colorado, for which paleoseismological work had provided estimates of magnitudes and dates of prehistoric surface ruptures. Additional individual faults or fields of liquefaction features can be included in the 2001 and future maps as paleoseismological results become available. The paleoseismological results are necessary because magnitudes and recurrence intervals of large earthquakes do not always match extrapolations from historical seismicity.

The importance of paleoseismology is shown by large characteristic earthquakes that are not extrapolatable from historical seismicity at the New Madrid seismic zone and Charleston, South Carolina. For New Madrid, the 1996 maps used a characteristic earthquake of Mw 8.0, based on Arch Johnston's isoseismal-based estimates. Paleoseismological data available at the time indicated a recurrence interval of 1,000 years. For Charleston, Johnston's estimated Mw is 7.3 and paleoseismological evidence indicated a recurrence interval of 650 years. Additional paleoseismological results since the mid-'90's from both areas indicate recurrence intervals of approximately 500 years.

The attenuation relations used in the 1996 maps are for a geologic site condition that corresponds to the NEHRP B-C boundary. This corresponds to a typical rock site at which strong motion data have been recorded in the western U.S. Relations of Toro et al. (1993) and Frankel et al. (1996) were given equal weights. The relation of Atkinson and Boore (1995) will be added for the 2001 maps. In addition, we will produce a map for a hard-rock site condition.

The 1996 maps of 2 percent exceedance probability in 50 years show similar probabilistic ground motion at New Madrid and on some parts of the San Andreas fault. This similarity has confused some recent critics of the maps. The similarity results from lower attenuation in the CEUS than in the West, and from higher CEUS stress drops, which produce stronger high-frequency motions. Both geographic differences are based on observations of CEUS isoseismals and recordings of small to moderate earthquakes. At this probability level, the largest earthquakes are being taken into account. Note that at the 10 percent exceedance probability, the San Andreas hazard is much higher than that of New Madrid. This difference reflects both the higher ratio of low-magnitude earthquakes on the San Andreas fault system, and the shorter recurrence interval of the largest San Andreas earthquakes compared to the largest New Madrid earthquakes.

Frankel showed estimates of the uncertainties of the values on the 1996 maps. The estimates were derived from Monte Carlo sampling among the input alternatives, which include re-sampled catalogs, different weights on the magnitude 3, 4, and 5 smoothing grids, characteristics earthquake magnitudes and recurrence times for Charleston, S.C., attenuation-function median curves, etc. Frankel had been able to construct suites of alternative hazard curves for a number of important cities. The uncertainty can be characterized by the ratio of the 85th percentile to the 15th percentile ground motions. The ratio is typically approximately 3, being larger where seismicity is sparse and smaller in more active areas.

In closing, Frankel listed some topics for possible discussion by the attendees. Logic trees for New Madrid and Charleston require specification of weights for different candidate magnitudes, recurrence intervals, and source zone geometries. The Atkinson-Boore attenuation relation needs to be weighted relative to those of Toro et al. and Frankel et al. Paleoseismological results published since 1996 show prehistoric Mw larger than 6.5 in Illinois and Indiana; the new results require an increase in the maximum magnitude that is assumed for this part of the craton.

Hazard along and near the Humboldt fault zone of Nebraska and Kansas may be underestimated in the 1996 maps, because the area has sparse low-magnitude seismicity but has had two historical earthquakes of magnitude approximately 5.

Quaternary tectonic faults

Rus Wheeler summarized results of a literature compilation and evaluation that was done with Tony Crone, as part of updating the 1996 national maps. Wheeler and Crone compiled published geologic (stratigraphic, structural, geomorphic, or paleoseismological) evidence for Quaternary tectonic faulting at 69 U.S. locales east of the Rockies. Others had compiled an additional seven locales in the states that straddle the Rocky Mountain Front, for a total of 76 faults, fault zones or systems, liquefaction fields, uplifts, and other features.

Of these 76 evaluated features, 15 represent confirmed Quaternary tectonic faults. Most of the 15 are in or near the central Mississippi Valley, coastal South Carolina, and the Boston-Washington urban corridor. Two of the confirmed Quaternary tectonic faults, the Meers and Cheraw faults, had already been incorporated into the 1996 maps. Some other confirmed Quaternary tectonic faults do not impact the maps, either because (1) estimated prehistoric magnitudes do not exceed local assumed M(max), for example, liquefaction features at Newbury, Mass., and in the central Virginia seismic zone; (2) recurrence intervals of liquefaction are too long, for example, Newbury; (3) the most recent documented surface rupture is too old, for example, the Goodpasture fault in Colorado; or (4) magnitudes and dates of individual prehistoric earthquakes are too poorly constrained, for example, the Thebes Gap – Benton Hills area, Mo. – Ill., the Fluorspar district of southern Ill., the Western Lowlands of Ark. – Mo., and the Cape Girardeau – Saint Louis area, Mo. – Ill. Approximately half of the 76 features were dismissed as either pre-Quaternary or not faults. For example, some are landslides. The rest of the features need more work before they can be either accepted or dismissed as Quaternary tectonic faults. Examples include the Brockton-Froid lineament of eastern Montana, several sites on large faults in eastern and western Kentucky that await trenching, and the Lancaster seismic zone west of Philadelphia. Future work on some of the known features and on others not yet recognized is likely to impact maps beyond 2001. Results are being assembled into a USGS Open-File Report and 2-4 journal papers, and will be made available digitally.

CHARLESTON SEISMIC ZONE

Earthquake chronology

Pradeep Talwani summarized the paleoearthquake chronology that he has assembled and submitted to the Journal of Geophysical Research. He assembled all available dates on paleoliquefaction features, calibrated them to convert them from radiocarbon years to calendar years, and correlated them to define seven paleoliquefaction episodes. The geographic distribution of paleoliquefaction sites that record a given episode allows estimation of the magnitude of the causal earthquake with respect to the 1886 shock of Mw 7.3. As previously noted by Obermeier in 1996, most of the paleoearthquakes appear to have been approximately similar in size to the 1886 earthquake. Earlier recurrence intervals are longer than later ones. An episode at 1600 yr. BP is recorded only northeast of Charleston, in the Georgetown, S.C. area, and might represent an earthquake of about magnitude 6 produced by a separate source. Liquefiable sediments exist between Georgetown and Charleston but do not appear to have liquefied, so the 1600 yr. BP liquefaction features are unlikely to represent distant effects of a large earthquake at Charleston. Another episode at 2000 yr. BP is recorded only southwest of Charleston, near Bluffton, and might represent either the distant effects of a large earthquake at Charleston or the near-field effects of a magnitude 6 produced by a separate Bluffton source. Depending on choice of paleoearthquakes, recurrence intervals range from approximately 500 years for the last three earthquakes to more than 600 years if the older episodes are included.

The picture that emerges from this and previous work by several authors is one of repeated large, characteristic earthquakes with little paleoseismological evidence of smaller liquefying shocks.

The source or sources of the characteristic earthquakes are unclear. Talwani summarized structures that might provide a basis for defining source zones of the Charleston characteristic earthquakes. (1) Several kinds of seismological, other geophysical, and geological evidence taken together can be interpreted in terms of two intersecting faults. The Woodstock fault strikes northeast and is offset several kilometers northward where it cross the northwest-striking Ashley River fault. (2) Several kinds of geomorphological evidence define a northeast-trending "Zone of River Anomalies" (ZRA) (see Marple and Talwani, Feb. 2000 Geol. Soc. Am. Bull.). The ZRA appears to be a linear zone of recent uplift, and its southwestern end coincides with the modern microseismicity near Charleston. (3) Regionally, the Charleston area lies within the South Georgia rift basin, which is itself within the Atlantic passive margin of crust that was extended during the Mesozoic. (4) Seismicity appears to cluster near possible plutons that have been interpreted from potential-field data.

Lastly, Talwani suggested a logic tree for sources. The tree distinguishes single faults from areal sources. The fault branch would be weighted 0.8, and the areal source branch 0.2. On the fault branch, the Woodstock-Ashley River faults would be weighted 0.7, and the ZRA 0.3. On the areal source branch, the South Georgia rift basin would be weighted 0.7, and the zone in the 1996 maps would be weighted 0.3. The resulting weights would be 0.56 for the Woodstock fault, 0.24 for the ZRA, 0.14 for the areal source of the South Georgia rift, and 0.06 for the areal source used in the 1996 maps.

Logic tree

Chris Cramer briefly presented his and Richard Lee's results of a logic-tree hazard analysis for the Charleston area, for which they obtained higher hazard than shown on the 1996 maps. The purpose of the analysis was to determine which aspects of the logic-tree model most influenced the result. Using Monte Carlo sampling of the alternative branches in the logic tree, he could produce alternative hazard estimates. Overall, the coefficient of variation (COV; standard deviation divided by mean) was 0.6. Component COV's attributed to elements of the model are 0.9 for fault location, 0.6 for recurrence, 0.4 for characteristic magnitude, and 0.3 for attenuation function. Uncertainty of the rupture length has little effect. Cramer discussed fault location and recurrence in more detail. Compared to the 1996 map, the sources modeled were generally more concentrated geographically. A small areal source increases the hazard in the center of the study area, around Charleston; enlarging the areal source to include liquefaction features up and down the coast increases hazard to the southwest, toward Georgia, but decreases the value of Charleston hazard.

Cramer used observed recurrence intervals based on the paleoliquefaction studies. Two alternatives, which assume lognormal recurrence intervals, were based either on the most recent recurrence intervals or on all of them. For the first alternative, Cramer obtained a median recurrence interval of 453 years and, with a standard deviation of 0.5, a mean recurrence interval of 513 years. For the second alternative, he obtained a median recurrence interval of 701 years and, with a standard deviation of 0.8, a mean recurrence interval of 963 years.

Thus, the most important considerations at Charleston are the choice of source configurations and the decision as to whether to emphasize the most recent recurrence intervals. Cramer distributed a handout that summarizes the trial logic tree.

With respect to the different possible sources of the large characteristic Charleston earthquakes, Arch Johnston presented results from his and Paul Bodin's analyses of descriptions of railroad track shortening that was observed immediately after the 1886 earthquake. The locations and orientations of shortened tracks, the opposed senses of shortening northwest and southeast of the highest isoseismals, and the direction of elongation of the innermost isoseismals, together argue for right-lateral motion on a fault that strikes north-northeast between shortened tracks of opposed senses. The deduced fault might be expected to have produced surface rupture and extended railroad tracks along its trace; neither was reported. Johnston suggested that the absence of such reports might be a result of swampy ground between the locations of shortened track, or of a deep rupture zone that did not break to the surface.

Sue Hough suggested that little would be gained by reevaluating intensity reports from the Charleston 1886 earthquake. She raised this point now because her remarks this afternoon, on her reassessment of New Madrid magnitudes, might lead attendees to wonder whether the magnitude of the Charleston 1886 earthquake should also be reassessed. She has reevaluated intensity reports of the 1811-12 New Madrid earthquakes, to produce estimated magnitudes smaller than the Mw 8.0 used in the 1996 maps. Hough had revised several of the New Madrid intensity reports downward because of the older tendency to assign a site the largest intensity value reported from it, because of improved recent understanding of the role of site effects, and because of a few older transcription errors. However, the Charleston earthquake of 1886 produced far more reports that were more uniformly spatially distributed than those of 1811-12, and, in 1977, Bollinger and colleagues had carefully reevaluated the 1886 reports using three independent evaluators.

Rus Wheeler noted that the recurrence intervals lengthen backwards in time, and suggested that this could be attributed to an incomplete mid-Holocene record, lower water tables before 2,000 years ago, or a change in fault behavior. In any of these cases, should the older recurrence intervals be used at all? Cramer suggested that the older, longer recurrence intervals should stay in the logic tree, albeit perhaps with a low weight, to include the possibility that the present recurrence interval will turn out to be another long one.

Don Wells suggested that probably the older part of the paleoliquefaction record actually is incomplete because of lower water tables before 2,000 - 4,000 years ago, following earlier suggestions by other workers in the area. Wells and his colleagues had developed three models in their attempt to estimate the large-earthquake recurrence at Charleston: (1) assigning all the liquefying earthquakes to the Charleston source, (2) having one of the earthquakes at a northern source, one at a southern source, and the rest at the Charleston source, and (3) combining, into a single earthquake, two of the groups of liquefaction features that formed at two similar times with overlapping uncertainties in their ages. In all models, Wells and colleagues discarded the older recurrence intervals as too long because of incompleteness. Cramer agreed, preferring to weight most heavily the 450 year interval obtained from the three most recent earthquakes.

There followed a lengthy but inconclusive discussion about how to weight the various source models. Questions included how much or how little to weight the various likely fault sources and how to constrain the boundaries of an areal source zone. There appeared to be a general sentiment for sources that are more areally concentrated than the source zone used in the 1996 maps. Frankel asked for opinions about earthquake rates and opinions on the logic tree and weights proposed by Talwani, either during or after the workshop.

SOURCES NORTH AND WEST OF THE NEW MADRID SEISMIC ZONE

Rus Wheeler set the afternoon's discussion of New Madrid in context by summarizing paleoseismological results from five other study areas north and west of the New Madrid seismic zone. (1) Work in the southern Illinois basin, which includes the Wabash Valley seismic zone and the region between St. Louis and Indianapolis, has defined epicentral areas of eight Holocene and latest Pleistocene earthquakes that were large enough to cause liquefaction. Estimated moment magnitudes range from approximately Mw 6 to 7.5, and dates are sufficient to constrain recurrence intervals. Thus, the southern Illinois basin, like the New Madrid seismic zone, can be incorporated into the national maps. In contrast, work in four other areas so far has established the occurrence of prehistoric earthquakes large enough to have produced surface ruptures and liquefaction, but magnitudes and dates of individual earthquakes are too poorly constrained to be included in the maps. These other areas are (2) the Western Lowlands of Arkansas and Missouri, (3) the St. Louis-Cape Girardeau map area, (4) the Thebes Gap (Illinois) – Benton Hills (Missouri) area, and (5) the Fluorspar District of southeastern Illinois.

NEW MADRID SEISMIC ZONE

Paleoearthquake chronology

Buddy Schweig summarized the paleoearthquake chronology of the New Madrid seismic zone. (Note that the zone does not include the prehistoric earthquakes that have been recognized during the past decade in southern Illinois, southeastern Missouri, and Indiana.) The 1811-12 liquefaction field is unique globally in its extent and in the size and number of individual features, with dikes that are often meters wide and collapsed areas the size of football fields. Results come from study of sand blows and dikes. Crosscutting relations, radiocarbon dates, and archeological artifacts provide age constraints. Ages and sizes of liquefaction features support correlations between individual features at different sites. Widespread liquefaction occurred in A.D. 1811-12, 1450, 900, and perhaps 500. Dating uncertainties allow recurrence intervals from 200 to 800 years.

Years ago the late Roger Saucier noticed that 1811-12 liquefaction features in the central section of the seismic zone were made of three fining-upward sequences of sand without intervening soils. Since then, Schweig, Tish Tuttle, and colleagues have observed this property throughout the seismic zone. They also found that sand blows dated at A.D. 900 contain three fining-upward sequences, but that sand blows dated at A.D. 1450 contain only two. The stacked, fining-upward sequences without intervening soils are the record of two or three strong shaking events that were separated in time by intervals long enough for sand to settle out of suspension, but short enough that soil-forming processes could not significantly modify the recently erupted sand. Furthermore, the stacked sequences are recognizable over large distances, so they are not attributable to aftershocks in the usual sense of the word. The single, less widely distributed, fining-upward sequences that would be produced by moderate earthquakes are few. Thus, the earthquakes in 1811-12, 1450, and 900 were pairs or triplets of large to very large earthquakes, were not clusters of many moderate earthquakes, and appear to be characteristic.

The Ambraseys curve, which plots distance to the farthest liquefaction feature versus magnitude, gives estimated magnitudes of 6.9, 6.7, and 7.6 for the earthquake sequences of A.D. 900, 1450, and 1811-12, respectively. These estimates are likely to be low because the sediments of the seismic zone are only moderately liquefiable. A lack of recognized older liquefaction features and a lack of large cumulative Quaternary tectonic deformation indicate that there is little evidence that the seismic zone was active at its present level before a couple of thousand years ago.

Joan Gomberg asked whether magnitudes estimated from the Ambraseys curve are extrapolations beyond the data, given that the 1811-12 liquefaction field is unique. Schweig agreed. Rus Wheeler pointed out that the Ambraseys curve depends on the distance to the farthest observable liquefaction feature, which is likely to be small and, for prehistoric shaking events like those at New Madrid, perhaps poorly preserved. In addition, the Ambraseys curve is likely to be dominated by small features that formed in the most highly liquefiable sediments, whereas the sediments at New Madrid are only moderately liquefiable. Accordingly, the magnitudes derived from the Ambraseys curve might be severe underestimates. Ken Campbell noted that this effect would be countered by lower attenuation in the U.S. midcontinent compared to the areas Ambraseys studied, many of which are in plate boundaries. Bob Herrmann suggested that the geographic distribution of liquefaction features should show a north-south asymmetry, because the thicker soil columns in the southern part of the seismic zone should damp out the higher frequencies.

Historic earthquakes

Sue Hough summarized the basis for her conclusion that the 1811-12 earthquakes had moment magnitudes in the mid-7's, not around 8 as estimated by Arch Johnston and as used in the 1996 hazard maps. An early version of her work, which contains estimated magnitudes in the low 7's, has been submitted to the Journal of Geophysical Research. Hough pointed out that there were four earthquakes large enough to cause liquefaction, including the largest aftershock. Liquefaction is influenced by duration in addition to strong motion, and the ground motion effects are the most direct evidence we have with which to estimate magnitudes. The reports that Hough and colleagues examined contain two transcription errors, a second-hand account, and a report of the largest aftershock instead of one of the three main earthquakes.

Hough pointed out that the shaken area was sparsely settled at the time of the earthquakes. The earthquakes happened less than a decade after the Lewis and Clark expedition. The few settlements were usually in river valleys, and there were almost no settlements west of the seismic zone. The town of New Madrid was washing into the Mississippi River even before the earthquakes. However, some towns were on limestone bluffs and suffered little or no amplification – Sainte Genevieve, Mo., sits on limestone between Cape Girardeau and Saint Louis and still contains about 50 buildings that predate the earthquakes, including some brick and masonry houses and many masonry chimneys. Nonetheless, amplification and site effects were a large component of many reports, and the reevaluation of individual reports attempted to take these effects into account.

Hough's most recent results are estimated magnitudes of 7.3, 7.0, and 7.5 for the December 1811, January 1812, and February 1812 earthquakes, respectively. These estimates are consistent with ordinary stress drops, likely fault areas, and the Mw 7.3 estimated for Charleston 1886.

Arch Johnston countered with the still-evolving basis for his magnitude estimates of around 8. Starting with Les Youd's work on liquefaction severity index (LSI), which relates distance to magnitude, Johnston showed that the New Madrid and Charleston earthquakes must have had very different magnitudes – LSI values of 100 occur only within 100 km of Charleston, whereas the same values are obtained 200 km from New Madrid. Johnston accepted that Hough had demonstrated problems with estimating intensity from isoseismals. He explained that Bill Bakun has developed a way to estimate epicenter and magnitude from point locations of intensity reports, to avoid the problems created by drawing isoseismals. Bakun and Johnston are collaborating to modify Bakun's methods to apply to the CEUS. They use a CEUS training set of earthquakes that have both instrumental magnitudes and intensity reports. For a given intensity, distances are considerably larger in the CEUS than in the West. They use the median distance for a given intensity level. Distance-median intensity points define a curve for the CEUS, whereas they fall on a straight line in the West. The CEUS curve projected inward to zero distance is three intensity units higher than the Western U.S. line for magnitude 5, and two units higher for magnitude 7. Johnston suggests this difference might indicate higher stress drops in the CEUS. The present form of the method appears to estimate CEUS magnitudes better than CEUS epicenters. When applied to Street's data for the December mainshock and aftershock and the January and February mainshocks, results are Mw 7.8, 7.2, 7.9, and 8.0, respectively. Using Hough's reassigned intensity values gives 7.8 and 8.1 for the last two earthquakes in the sequence. Johnston argues that the three New Madrid mainshocks were probably of Mw 7.8-8.1.

GPS models

Prior commitments prevented Seth Stein and Andrew Newman from attending to present their arguments for New Madrid magnitudes of approximately 7. They were able to prepare a handout, which was distributed. In their absence, Joan Gomberg presented an overview of GPS models of the CEUS, drawing on results presented in a 1999 Science paper by Newman, Stein, and coauthors, and by them and several others at a January, 2000 workshop at the University of Memphis. Some of these results are described in more detail in the January workshop minutes at http://www.ceri.memphis.edu/usgs/hazmap/20jan00minutes.shtml. The attendees at the January workshop have prepared a summary for submittal to EOS, and preprints were distributed.

The observables from GPS are monument velocities relative to some assumed fixed monument or reference. Midcontinent GPS velocities, relative to a model of stable North America, are small and uncertainties are large. Interpretation of these velocities in terms of fault or localized slip rates requires that some model be invoked. Perhaps the most commonly invoked model, used both because of its simplicity and because of its appropriateness in plate-boundary environments, assumes the driving deformation rate is constant and is relaxed by slippage along a fault of finite width and infinite length (e.g., as in a plate-boundary). Moreover, the driving deformation arises from the relative displacements of the blocks cut by the fault. Use of this model implicitly produces the lowest possible fault slip rates, because the measured deformation is assumed to equal the driving displacements that also must equal the slip across the fault. The appropriateness of this model in an intraplate setting like New Madrid is questionable for several reasons. First, the New Madrid area is not a plate boundary, driven by relative displacement of adjacent plates, but a stress-driven zone of weakness. The New Madrid fault system also has finite length, with a length that is probably no more than several hundred km. Finally, even data from a plate boundary (i.e., the San Andreas) show that the driving deformation rate is not constant between major earthquakes. However, a number of alternative models have been developed, that permit significant earthquake slip on finite-length faults that does not result in surface displacements of comparable size. These have been applied to New Madrid by Kenner and Segall, and the models do reproduce the first order observations.

Logic tree

Chris Cramer presented a logic tree for New Madrid hazard. He explained that a logic tree is the best way to incorporate knowledge-based uncertainty (as opposed to random uncertainty) and to determine the effect of the uncertainty on the final hazard. The logic tree is described at http://www.ceri.memphis.edu/usgs/hazmap/logictree.shtml. Cramer explained the various branches of the tree and examined the sensitivity of hazard to various choices of paths through the tree. The preferred map given by the logic tree shows the means or expected values of probabilistic ground motion, and the preferred map resembles the 1996 maps. The hazard is most sensitive to which fault or faults are considered seismogenic, and about equally sensitive to choice of attenuation relation, characteristic magnitude, and recurrence interval of the characteristic earthquake. The COV's for the source and recurrence interval are two-thirds to half of the respective values obtained at Charleston, S.C. Uncertainty in the rupture length has little effect, as with the Charleston model.

Most of the few opinions voiced about choice of seismogenic faults favored following the alignments of historical seismicity (Gomberg, Wheeler), and, thereby, reducing the effect in the model of graben-border faults. Arch Johnston suggested the assumption of faults that are centered on the liquefaction field.

Pradeep Talwani summarized results from a releveling study of a seismically active area in Belgium. The overall motion is mostly incoherent, which would be consistent with numerous small blocks that are moving up and down. Talwani speculated that New Madrid might behave similarly, as a strained crustal volume with earthquakes occurring at stress concentrators such as plutons or intersecting faults.

The magnitude of the 1811-12 earthquakes remains an open question. Art Frankel asked for opinions on various combinations of recurrence intervals and magnitudes, hoping to focus discussion on choices of mean values. Gail Atkinson noted that none of the appropriate attenuation relations is constrained by data above magnitude 7.5, and higher magnitudes would require extrapolation. Therefore, the magnitude chosen should be the one that can reproduce the observed intensities from whatever attenuation relation is chosen. Most agreed with this need to close the loop between magnitudes, intensities, and attenuations.

Wednesday, June 14

OTHER SOURCES

Wabash seismic zone, southern Illinois basin

Rus Wheeler summarized how the southern Illinois basin, including the Wabash Valley seismic zone, had been treated in the 1996 maps, as well as new findings that require a change in the treatment. The entire Illinois basin spans most of Illinois, Indiana, and Kentucky, and parts of Missouri and Tennessee. Within the basin, the Wabash Valley seismic zone straddles the southern part of the Illinois-Indiana border. The basin lies within the craton, for which Mw(max) was set at 6.5 for the 1996 maps. At the time of the 1996 maps, eight prehistoric earthquakes in the southern Illinois basin were known to have been large enough to cause liquefaction, but magnitude estimates were available only for the four that clustered in the Wabash Valley seismic zone. Two of these magnitudes were Mw 7.1 and 7.5, exceeding the local Mw(max) of 6.5. Accordingly, for the 1996 maps, a source zone was drawn to include the four clustered epicentral areas, and Mw(max) was set at 7.5 inside the zone. Since then, the other four prehistoric earthquakes have been estimated to have equaled or exceeded 6.5. Wheeler proposed expanding the zone four-fold in size to include all eight epicentral areas, with Mw(max) 7.5 inside the zone and 6.5 outside. In the future, the zone could be expanded as needed to include any additional earthquakes that might be found to have exceeded 6.5.

Art Frankel reported that a Gutenberg-Richter plot shows that these eight prehistoric earthquakes are consistent with the historical seismicity in the southern Illinois basin. The plot predicts a mean recurrence interval of 1,700 years for earthquakes larger than Mw 6.5. The paleoseismological results indicate six of this size in the last 12,000 years, which about matches the recurrence interval inferred from the plot, and indicates that an earthquake larger than 6.5 may still be possible. The enlarged zone of Mw(max) 7.5 that Wheeler proposed would increase the ground motion at 2 percent exceedance in 50 years by about 10 percent.

The ensuing lengthy and enthusiastic discussion raised many points, chief among which turned out to be Gail Atkinson's observation that the occurrence of, say, a 6.8 anywhere in the craton for which Mw(max) was still as low as 6.5 would undermine the credibility of the 2001 maps. Frankel recalled that 6.5 was the value chosen for cratonic Mw(max) at a 1994 workshop, and that setting Mw(max) as high as 7.5 for the rifted rim of North America was controversial then. Wheeler noted that Arch Johnston's 1994 global compilation had found that cratons have had historical earthquakes as large as 6.8 +/- 0.3, but rifted rims of stable continental regions have had larger historical earthquakes. Therefore, the two parts of the North American stable continental region do appear to need different Mw(max) values. However, Johnston's finding supports an Mw(max) larger than 6.5 for the craton. Attendees appeared to accept that 6.5 is now seen as too low for the craton. Wheeler offered the straw man of increasing the cratonic Mw(max) to 7.0 and retaining something like the 1996 source zone with Mw(max) 7.5 to enclose the 7.1 and 7.5 in the Wabash Valley seismic zone. Alan Kafka and Frankel suggested that it would be worthwhile to characterize the uncertainty of the location of the boundary between the rifted rim, with Mw(max) 7.5, and the craton, with smaller Mw(max).

Ivan Wong asked whether a truncated exponential magnitude model was suitable for the Wabash area. Art Frankel replied that the recurrence of the larger prehistoric earthquakes there was consistent with that model, but that this was clearly not the case at New Madrid and Charleston. At New Madrid and Charleston, the paleoseismologically-determined rate of the large, characteristic earthquakes is much higher.

Eastern Tennessee

Martin Chapman summarized the eastern Tennessee seismic zone, the most active in the Appalachians but lacking an historical earthquake larger than m(b) 4.6. The zone is defined by microseismicity. Seismicity occurs at depths of 5-20 km, beneath the Paleozoic rocks of the Appalachian thrust sheets. Earthquakes are spatially correlated with potential-field anomalies. The large spatial extent of low magnitude seismicity suggests that a large crustal volume may be stressed. However, a statistical test indicates no clear basis for limiting M(max) on the basis of historical seismicity. Chapman concluded that no changes are needed from the way the zone was treated in the 1996 maps.

Northeastern U.S.

Rus Wheeler reported that he and John Ebel agree that no new developments in the Northeast require changes in the way the region was treated for the 1996 maps. The main new result from the region stems from work by Ebel that moves the most likely location of the 1727 Newbury, Massachusetts earthquake onshore from its previous offshore location, and increases its estimated magnitude from m(bLg) 5.0 to m(b) 5.6.

Quaternary faults in Toronto

Arsalan Mohajer presented results from the Toronto area that he suggested might also apply to the Northeastern Ohio seismic zone near Cleveland. Outcrops in the eastern Toronto metropolitan area, near the Pickering nuclear power plant, contain faults that cut both bedrock and Quaternary strata. Whether the Quaternary slip is of tectonic, glaciotectonic, or glacial rebound origin is in dispute, but work continues. The faulted outcrops lie on the Niagara-Pickering magnetic lineament. The lineament has been traced southwestward on aeromagnetic and gravity maps into the Akron (Ohio) magnetic lineament and the Northeast Ohio seismic zone, near the Perry nuclear power plant. Mohajer urged further paleoseismological study, both in the Toronto area and in the Northeast Ohio seismic zone, because of the population and critical structures that are concentrated in both areas.

Art Frankel and Rus Wheeler responded that we are interested in the various published reports on this area, including any conclusions of the Geological Survey of Canada. Frankel pointed out that the computational methodology used for the U.S. national maps requires estimates of the magnitudes and recurrence intervals of individual prehistoric earthquakes before an individual fault, as opposed to an areal source zone, can be incorporated into the maps. This requirement applies throughout the map area, including the Northeast Ohio seismic zone.

ENGINEERING CONCERNS

Design maps

The 1996 USGS ground motion maps were modified for use in building codes. The modified maps were prepared by the USGS and are based on the recommendations of the Building Seismic Safety Council's (BSSC) Seismic Design Procedures Group (SDPG). The SDPG-recommended maps, the Maximum Considered Earthquake (MCE) Ground Motion Maps, are based on the USGS, 2 percent probability of exceedance in 50 years, probabilistic maps with additional modifications incorporating deterministic ground motions near some major faults. The MCE ground motion maps are available at http://geohazards.cr.usgs.gov/eq/, as well as on a CD-ROM. There are three sets of design maps. (1) The 1997 NEHRP Recommended Provisions map set consists of 32 large-scale maps. (2) The 2000 International Building Code (IBC) Maps are derived from the NEHRP maps with changes only in map scale and the number of maps in the map set. This same set is incorporated in the national standard ASCE 7, "Minimum Design Loads in Buildings and other Structures." (3) The 2000 International Residential Code (IRC) Map is also derived from the NEHRP maps, simplified into site categories defined by specific contours on the MCE maps.

E.V. Leyendecker noted that the goal of engineering design is to achieve public safety at an economical cost. Buildings will continue to be constructed using the most recent published ground motion maps and other criteria. Accordingly, engineers are best served if hazard mappers make the best seismological and geological estimates that we can now, while incorporating existing uncertainties. A complete review and revision cycle for the design maps takes approximately three years, and probably the next code revision will occur in about six years at the earliest.

A uniform hazard response spectrum can be approximated from the 0.2 s and 1.0 s spectral ordinates. Leyendecker illustrated the construction of an approximate spectrum using the two ordinates. This approximation works well for San Francisco, for example, but less well for the CEUS because the CEUS spectrum continues to rise with decreasing period to 0.1 s.

Leyendecker described the value of deaggregating the hazard to identify the magnitudes and distances of the earthquakes that dominate the estimated hazard for a given site. With knowledge of the dominant magnitudes and distances, one can more readily estimate durations and construct time histories. He showed sample deaggregations for San Francisco and Saint Louis. Deaggregations for numerous cities, as well as a custom-deaggregation utility, are available at http://geohazards.cr.usgs.gov/eq/.

Leyendecker also explained the choice of 760 m/s for a site condition nationwide in the hazard maps. In the western U.S., the available ground motion attenuations are based on empirical data (variation of ground motion with distance) and can be used for a site condition of 760 m/s in the top 30 m without too much difficulty. In the CEUS, the existing ground motion attenuation relations are in terms of hard rock, which has a much higher shear-wave velocity. It was believed these latter attenuations could not be confidently extrapolated for materials with shear-wave velocities less than 760 m/s without encountering nonlinear site effects. Accordingly, the common site condition of 760 m/s in the top 30 m was selected for the entire U.S. The map values must be adjusted for local site-condition variations. It is anticipated that the 2001 maps will include additional maps for a hard-rock site condition in the CEUS.

Joe Hunt discussed production of the 1997 MCE maps from the perspective of the BSSC. The 1997 design maps represent at least three changes from previous design maps. (1) They use 2 percent exceedance probability in 50 years instead of the previous 10 percent. These are considered collapse-level ground motions. (2) They use spectral accelerations at 0.2 s and 1.0 s instead of the previous peak acceleration. (3) They use the 1994 NEHRP site condition classes instead of the previous 1991 NEHRP classes. The performance goal nationwide is life safety and a low likelihood of building collapse for ground motions larger than the design ground motion. Engineering experience with earthquake damage indicates that properly designed structures, using current code design criteria, can withstand motions larger than their design motion without collapse. The ratio of estimated collapse motion to the design motion is termed the seismic margin. By using an estimate of a factor of 1.5 (considered a lower-bound value) for this margin, the collapse level was chosen to be the previously indicated 2-percent /50-year ground motions, and the result was design ground motions that are two-thirds of these values (collapse ground motions divided by 1.5, the seismic margin). Hazard curves have different slopes for CEUS and western U.S. cities, with the result that as probabilities of exceedance decrease, ground motions for cities in the western U.S. show little increase while ground motions for cities in the CEUS show considerable increase. In the CEUS, design for 10-percent/50-year ground motion would provide little protection if 2-percent/50-year ground motions occurred. Use of the larger 2-percent/50-year ground motion as a collapse prevention load, divided by the margin of safety, is intended to provide a uniform reliability against structural failure.

The new design ground motions are clearly larger at New Madrid and Charleston than the previous design values. Elsewhere, new values may be larger or smaller than the old values, but in areas with low hazard, the change has little impact. In some areas, largely in the western U.S., the design ground motions are constrained by deterministic ground motions based on prior earthquake experience and engineering judgement.

Hunt listed problems that need more work. The geologic site condition classes need better site coefficients. Sensitivity studies could lead to better understanding of the uncertainties in the maps and their causes. The correlation between ground motion and damage in different types of structures is poorly understood. Deterministic seismic sources, CEUS attenuation, representative earthquake histories for use in design, and the performance levels for structural design all need better definition. The seismic margins that are inherent in the design process require more study, as do ground motions with periods longer than 1 s.

Seismic piezocone method

Paul Mayne summarized the use of seismic piezocone measurements to estimate liquefaction susceptibility of sediments in situ, and to estimate the magnitude of the earthquake that would be necessary to cause liquefaction of the sediments. By applying the method to existing paleoliquefaction features, it may be feasible to estimate the magnitudes of preinstrumental earthquakes from geotechnical properties of the liquefied sands. Mayne and colleagues are gathering data at test sites in Charleston, S.C., Memphis, northeastern Arkansas, and southeastern Missouri. Calibrating sites in Japan and California are of uncertain applicability to the CEUS. Recorded strong motion data would aid calibration.

CONTINUATION OF "OTHER SOURCES"

U.S. earthquake registry/compendium

Arch Johnston described his vision of a uniform moment-magnitude collection of all earthquakes at or above the felt threshold for the entire U.S. He prefers the terms "registry" or "compendium" because each earthquake would be represented by considerably more information, including original data, than is typically contained in current catalogs. At least half of the felt earthquakes are non-instrumental, even up to the first half of the twentieth century. There has never been a combination of instrumental and pre-instrumental earthquakes into a uniform moment-magnitude catalog. Currently he is funded to make such a registry or compendium for the central 20 states. He outlined a process involving collaborators who could add similar material for the western and eastern states, with all working to common standards to insure nationwide compatibility.

Humboldt fault zone, Kansas-Nebraska

Rus Wheeler summarized the geologic setting. The youngest rocks known to be deformed by slip on the fault zone are about 290 m.y. old. Art Frankel explained that the hazard presented by the fault zone might be underestimated in the 1996 maps. Two poorly located historical earthquakes of magnitudes 5.0-6.0 occurred near the northern part of the fault zone, but seismicity is sparse at lower magnitudes. Frankel proposed drawing an areal source zone around the magnitude 5's and nearby seismicity, to prevent diluting the local hazard during the seismicity smoothing computation that is used in the maps. Frankel showed the results of using such a zone. However, there was little enthusiasm for changing the way the region was treated in the 1996 maps.

ATTENUATION AND GROUND MOTION

Ken Campbell proposed a method for developing a hybrid empirical attenuation relation in regions with few strong motion recordings, such as the CEUS. This would be an alternative to attenuations based on stochastic models. The strategy would be to rely on relative differences between a host region with many recordings, such as California, and a target region with few recordings. One would select an empirical attenuation model for soft rock from the host region, develop seismological models for the host and target regions, and use the seismological models to adjust the empirical attenuation model to the target region. In this way, the resulting attenuation model for the target region would have near-source characteristics built in. Weaknesses of the suggested strategy include a lack of reliable seismological models, the assumed similarity of near-source characteristics in host and target regions, and an assumed similarity of the scaling relations in both regions. Campbell showed some encouraging examples and comparisons. The hybrid model shows more near-field saturation than other models. It compares well with the Lawrence-Livermore National Laboratory composite model for PGA, but would be more appropriate for extrapolation to Mw 8.

Gail Atkinson reviewed competing CEUS attenuation relations and presented some new results. She noted that the competing relations have similar attenuation rates with distance, and differ mainly in absolute level and in how they model the source. The main effect of this difference is in long-period ground motion, where the two-corner Atkinson-Boore 1995 relation estimates lower hazard than the one-corner relation of Frankel et al. 1996. The difference is small at all frequencies for magnitude 4.5, but large at frequencies of 2 Hz and less, for magnitude 7.5. For 5 Hz, hazard at St. Louis is dominated by a hypothetical magnitude 5.25 earthquake at 7 km distance, and the two models predict about the same hazard; at 1 Hz, hazard is dominated by a hypothetical magnitude 7.75 at 100 km distance, for which the two models differ by a factor of 2. Stochastic simulations of magnitude 6 and smaller earthquakes at large distances show good agreement with eastern North American (ENA) ground motion data at 0.2 sec, for both models; at 1.0 sec the Atkinson and Boore model matches the data, while the Frankel et al model overpredicts the data. Atkinson examined California data and found a two-corner effect there, as well. She also found that the California source model nearly matches the ENA source model. She concluded that empirical California ground motion relations can be modified for use in ENA, by using simple factors to reflect regional differences in crustal amplificaton and attenuation. She recommended that the 2001 maps use 3 sets of ground motion relations: the Atkinson and Boore 1995 relations (2-corner stochastic model), a 1-corner stochastic relation (either Frankel et al., 1996 or Toro et al., 1993), and a modified California empirical relation.

Art Frankel agreed with Atkinson about the need to add the Atkinson-Boore 1995 model for the 2001 maps, with a weight of at least 1/3. However, he showed some data that do not appear to be consistent with the two-corner model. The Nahanni, Ungava, Loma Prieta, and other California data do not appear to have corners where the model would predict them. However, Atkinson pointed out that the corners could not be properly determined based on the teleseismic data shown, which are reliable only for frequencies of 1 Hz and less, whereas the predicted corners are at higher frequencies. Joan Gomberg noted that it is dangerous to generalize from individual earthquakes because of slip variability and azimuthal effects. Frankel's opinion is that it is fundamentally risky to take regional recordings of older earthquakes and extrapolate back to characterize the source. He asked whether Campbell's hybrid method is already in a form that we can use for the 2001 maps.

Bob Herrmann summarized some of his results on high-frequency scaling, site effects, intensity, and high-frequency ground motion in the central U.S. (CUS). A goal is to generalize a model to allow extrapolation to higher magnitudes than have been recorded instrumentally in the CUS. Computing the effect of the thick filling of the Mississippi embayment depends critically on the depth dependence of Q. The embayment filling is asymmetric north-south, thickening southward. Accordingly, adding the filling to the national maps would produce resonances in the northern, shallow part of the embayment, attenuation in the southern, deep part, and corresponding north-south asymmetry in liquefaction and other effects. If the 1999 results of Dave Wald are correct, then older intensity maps overestimate peak motions because the isoseismals tend to follow the most distant reports of a given intensity instead of something like a median distance. This overestimation would impact loss estimation. Regional CUS ground motion indicates motions about 1.5 times larger than predicted by Atkinson-Boore 1995 at distances of 200-500 km. This effect would only slightly decrease magnitude estimates of the 1811-12 New Madrid earthquakes, but it also favors slightly different distance scaling for the CUS than would be used for the northeastern U.S. and southeastern Canada. If the attenuation relation of Toro and McGuire is used in the 2001 maps, we should collaborate with them to develop a stochastic forward model. Although the standard FEMA 273 procedure can be used in most of the U.S., it should not be used in areas of deep soils, such as the Mississippi embayment.

Ken Campbell pointed out that site factors that are based on California data reflect a velocity gradient that continues to great depths. A site underlain by high velocity rock at shallow depth would behave very differently. Herrmann agreed, noting that the FEMA 273 procedure should not be used in much of the CUS. Sue Hough noted that Wald's peak accelerations were based on intensities from Tri Net, and that Trifunac and Brady systematically give lower peak accelerations for a given intensity than Wald.

Chuck Mueller reported on his characterization of the effects on ground motion of the seaward thickening wedge of Coastal Plain sediments and rocks on the Atlantic and Gulf of Mexico seaboards. The strata get younger seaward and the relative age differences mapped at the surface persist at depth. Thus, we might expect relative velocities and Q differences that are seen between sites at the surface to persist at depth, but to diminish downward. This expectation indicates the feasibility of mapping site effects at a regional scale, based on surface geology, its extension down-dip, and depth to basement. This would be important in assessing hazard throughout the Coastal Plain. Mueller used surface geology and depth-to-basement information obtained from the literature. He developed power-law Vs- and Qs-versus-depth functions for each of six surface geology units. Then, looping over a grid of sites, he calculated site response for various ground motion parameters, magnitudes, and distances, using quarter-wavelength approximations. Haskell-Thompson calculations demonstrate resonance, but Vs and depth are too uncertain to lend confidence in where amplifications and deamplifications would occur geographically. Deamplification is large atop the extremely thick sediment pile in the lower Mississippi River valley.

There was some discussion about characterizing the Mesozoic basins that underlie the Coastal Plain, about vertically incident waves, and about the desirability of including surface waves. Bob Herrmann reported complexities around 10 Hz that should not present problems at 1-10 Hz. Art Frankel showed a recording from the Fort Pillow station that shows trapping in sediments, with a significant surface-wave effect at 2 Hz.

GENERAL DISCUSSION

Summary

Art Frankel summarized some main points of the workshop, emphasizing that no decisions have been made yet. (1) The Charleston logic tree identifies many variables, and we heard a proposal for a greater geographic concentration of sources than was used in the 1996 maps. (2) There is disagreement about intensity-based estimates of magnitudes of the New Madrid earthquakes. Recurrence is uncertain because the A.D. 1450 sequence may have been of lower total moment than the 1811-12 or A.D. 900 sequences. (3) There is a need to increase Mw(max) for the craton, and to estimate the uncertainty in the location of the boundary between the craton and the extended rim of North America. (4) It remains uncertain whether the Humboldt fault zone requires special treatment. (5) There is a need for a CEUS catalog that uses a uniform magnitude. (6) It would be desirable to map uncertainty in the hazard, or at least to estimate uncertainty for individual sites. (7) How should the 2001 maps incorporate the Atkinson-Boore 1995 attenuation relation? (8) The hybrid attenuation relation proposed by Campbell is distinct from existing relations. Should it be included in the 2001 maps, and if so, how? (9) The 2001 maps will include a hard rock map. (10) Hazard maps that include amplification are in the future. (11) It is important to close the loop that links intensities, magnitudes, and attenuation. (12) Modeling of finite CEUS faults should be calibrated against data.

CORS GPS

Will Prescott observed that in the CEUS, the maps are driven by historical earthquakes, which have long recurrence intervals. Accordingly, we don't know whether we have identified all possible sources of large earthquakes. Searching the entire nation with present paleoseismological methods would take a long time. Prescott proposed seeking additional sources by utilizing the network of Continuously Operating Reference Stations, a nationwide GPS network that is being established for navigation. Currently CORS includes 140 stations, with three being added per month. Although these are not highly stable stations, they are many and the data are free except for an analyst's time. Prescott suggested determining velocities for many sites, selecting the few with anomalously large velocities, and attempting to verify their velocities by comparison to nearby sites. Already five or six stations have velocities well above noise levels. Prescott presented a probabilistic argument by which the expected increase in the number of CORS stations will raise to attractive levels the likelihood of observing a useful anomaly.

A questioner asked what we would do if we found a high velocity that could not be discounted. How would we estimate the seismic potential?

Other

Gail Atkinson and others approved of Art Frankel's summary. Sue Hough observed that closing the loop between intensity, magnitude, and attenuation will require reassessing the original felt reports. Arsalan Mohajer asked whether the cratonic source(s) in Toronto and northeastern Ohio were not worth further examination. Frankel agreed, noting that a first step should be thorough geologic study to determine whether the exposed faults are tectonic. Even if they are, they will hard to deal with without a recurrence interval. Norm Hester asked how we are reaching out to the users of the maps. Frankel replied that we have not addressed the issue of scenario earthquakes, but there is interest in it. We are always ready to discuss with users how we make the maps. Some of us will be doing this with the Washington state Department of Transportation, and the AASHTO codes may incorporate seismic hazard provisions.

APPENDIX

After the meeting Art Frankel provided an outline of his summary statement. We append it here, with the addition of numbers in parentheses that key to the numbered sentences in the summary paragraph on p. 15-16.

SOURCE ISSUES

1. Use logic tree to describe Charleston, SC source

   a. magnitude range (1)

   b. recurrence times (1)

   c. geometry- sentiment of workshop participants is to use a smaller areal source zone plus alternative models with Charleston-type earthquakes confined to Woodstock fault and Zone of River Anomalies (1)

2. Use logic tree to describe New Madrid Source

   a. magnitude (Mw7.25 to just above 8.0; preferred value around 7.6-7.7?) (2)

b. recurrence time (latest paleoseismological evidence indicates about 500 years mean rate) (2)

c. geometry: don't use fictitious faults from 1996 maps, multiple models: consider putting faults along current seismicity

3. Adjust Mmax zones

a. make Mw(max)=7.5 zone larger for Wabash valley zone, based on paleoearthquakes

b. make Mw(max)=7.0 for craton (3)

c. Consider uncertainty in craton-extended rim M(max) zones by logic tree with *somewhat different boundaries* (3)

4. Examine effect of using areal source zone for Nemaha Ridge rather than smoothed seismicity. Workshop participants not enthusiastic about changing to areal zone there (4)

5. Develop maps of uncertainties derived from Monte Carlo simulations (6)

GROUND-MOTION ISSUES

1. Include Atkinson and Boore 1995 attenuation relation (7)

2. Consider including hybrid attenuation relation of Campbell if it is put in a form we can use (8)

3. Produce hazard map of CEUS for hard-rock sites, in addition to B-C boundary sites (9)

4. Need to close loop between observed intensities and predicted ground motions from attenuation relations (11)

5. Need to incorporate finite-fault effects in attenuation relations for CEUS (12)

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