OVERVIEW OF LIKELY CONSEQUENCES OF A MAGNITUDE 6.5+ EARTHQUAKE IN THE CENTRAL UNITED STATES

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ABSTRACT

A very real threat is posed to developed urban areas of the United States by three distinct seismic sources zones, located in the upper Mississippi Embayment, along the Wabash Valley, and beneath south central Illinois. The most likely damaging earthquake is a Magnitude 6.0 to 6.8 event, which has a 25 to 40% probability of occurrence in the next 50 years. This risk is much greater than other places, like California, because the basement rocks are less fractured and seismic energy is conveyed over 10X more efficiently than in California. The impedance contrast between the unfractured basement rock and the unconsolidated alluvial cover creates a situation promoting more site amplification than any other location in the world. A quake in the upper end of that expected range (M>6.5) could cause unprecedented damage to the American Midwest, because the region is criss-crossed by numerous pipelines, commercial transportation corridors, power transmission grid network, telecommunications networks, and so forth. It is impossible to accurately gage the potential economic impact of such an event, because it would be unprecedented, and many human factors, such as the public's perception of the disaster and the time-to-recover from such a widespread catastrophe, are impossible to manage or estimate with any reliability. Recent natural disasters have shown that the role of the news media in influencing the public's perceptions of the disaster recovery is growing each year. These perceptions tend to control the ultimate extent of the loss because people refrain from economic activity (spending) until the perceived crisis is concluded. Scientists, engineers, emergency responders, and relief agencies are all encouraged to work with the news media in any natural disaster, to provide cogent explanations of recovery plans and operations, which can serve to encourage the actual recovery.

INTRODUCTION

The New Madrid Seismic Zone (NMSZ) was responsible for over 2000 earthquakes in 1811-12, felt throughout the upper Mississippi and lower Ohio River Valleys, when very few settlers lived west of the Mississippi River (Fuller, 1912). At least four of these earthquakes had surface wave magnitudes (M_s) of ~8+ (Nuttli, 1973; 1987), which are now believed to have been moment magnitudes (M) of between 7.0 and 7.5 (Bakun and Hooper, 2004). M6.0-6.2 quakes occurred at either end of the NMSZ in 1843 (Marked Tree, AR) and 1895 (Charleston, MO). Despite these events, the seismic threat posed by the NMSZ was not included in any of the region's municipal building codes until 2002, when St. Louis and St. Charles Counties in Missouri adopted the International Building Code (IBC).

In 1973 the NMSZ was more-or-less “re-discovered” during geologic studies for a nuclear power plant in West Memphis, AR, which came under review by the Nuclear Regulatory Commission (NRC). Soon thereafter (1974) the NRC engaged the advice and expertise of the USGS to assist in regional monitoring (Russ, 1982). These monitoring activities enlarged to include regional evaluations of relative seismic risk after an earthquake prediction by Iben Browning in December 1990, which garnered national attention (Spence et al., 1993).

Between 1979-99 the Wabash Valley Seismic Zone was investigated and eventually recognized as another seismic source zone (Bristol et al., 1979; Bear et al., 1997), although it has not been monitored as closely as the NMSZ (Fig 1). The WBVSZ is thought to be responsible for M 5+ quakes in 1968, 1987, and 2008. An amorphous zone of active seismicity also exists in South Central Illinois (McBride et al., 1997), which has spawned M 5+ quakes in 1838, 1857, and 1891. These seismic source zones are shown in Fig. 1.

In 2002 the U.S. Geological Survey released new earthquake probabilities for the New Madrid Seismic Zone, based on recent paleoseismic studies (Tuttle, et al., 2002). A magnitude 6.0 or greater earthquake has an estimated 25-40% chance of occurrence in the next 50 years. Such an earthquake could pose serious risk of damage to schools and masonry buildings between Memphis and St. Louis. The USGS also estimates a 7% - 10% chance of a Magnitude 7.5 – 8.0 earthquake occurring in the next 50 years (equal to the four largest quakes in 1811-1812).

DISCUSSION

Shaking Intensity versus Distance

The most troubling aspect of Midwestern quakes is the severe site amplification that exists in alluvial-filled valleys and dissected loess-covered uplands (Anderson et a., 1996). This is because of the marked impedance contrast between the unconsolidated alluvium and aeolian loess (Vs ~ 185 m/sec) and the less fractured Paleozoic age basement rocks, which typically transmit shear waves (Vs) at a speed of ~2800 m/sec (Chung, 2007). This means that seismic energy travels much farther and is felt more severely in the Midwest than in regions subject to more tectonic deformation, like California (Fig. 2). If the alluvial or aeolian sediments are more than 12 to 15 m thick, site amplification can be magnified by as much as 1300% for M6 earthquakes occurring 200 to 300 km from their source (Rogers, Karadeniz, and Chung, 2007). This creates a situation making Midwestern quakes much more lethal than California quakes of equal source magnitude, because there is less damping of seismic energy.

Potential Economic Impact of Soil Liquefaction

Liquefaction is a failure mechanism by which cohesionless materials (sand and silt) lose shear strength when the pore water pressure equals the effective confining stress. It is usually limited to the upper 50 feet and typically occurs in silt, sand and fine gravel. Recent sand blows dot the landscape surrounding New Madrid, MO, testifying to massive liquefaction, across a larger land area than any other US earthquake (Fuller, 1912). Recent studies by Chung and Rogers (2009) predict massive liquefaction could occur in the Mississippi and Missouri River flood plains for Magnitude >6.5 quakes emanating from the NMSZ, WVSZ, or SCI areas, where the depth of saturated alluvium exceeds ~18 m. Loess covered upland areas would be at far less risk for liquefaction. Though their main spans are supported on concrete caissons extending into the underlying bedrock, the simply-supported approach spans of most highway and railroad bridges are vulnerable to collapse if the driven piles supporting them tilt (lurch) in response to localized liquefaction. Fiber optic cables strung across these same bridge corridors bridges would also be severed in this scenario. The major river valleys are filled with old channels, cutoffs, and oxbows. Many of these features have been infilled to support development. Transportation infrastructure crossing such fills would be at greater risk because these areas can be expected to shake more violently than adjacent portions of the flood plains.

Shaking intensity varies according to underlying geology

Shaking Intensity is controlled by a factor called 'Seismic Site Response.' The type, depth, and size of fault, combined with physical properties of the Earth's crust and geophysical properties of overlying surficial soils, all combine to affect the seismic site response. Site response is used to describe the fundamental period of vibration and lateral forces generated by a typical earthquake at any particular site. The thickness of unconsolidated soils also affect the peak ground acceleration that can be generated at any given site, as shown in Fig. 3. The potential impact of soil thickness on shaking intensity is often portrayed in response spectra. A response spectrum is a plot of the maximum amplitudes of simple oscillators of varying periods (e.g. consider series of inverted pendulums of increasing height) produced by a recorded or assumed ground motion. Figure 4 shows the effect of soil thickness in the lower Missouri River floodplain on the response spectra. This illustrates the variation in expected spectral acceleration with alluvial thickness in the St Louis area.

As a consequence, the alluvial thickness is the single most important factor in expected seismic site response in the Midwest. Future seismic hazard maps for the Midwestern US will likely take the general form presented in Fig 5, which is based on the areal distribution and thickness of Pleistocene and Holocene age alluvial filled floodplains.

Likely impacts of most probable quake

The probability of a moderate earthquake occurring in the New Madrid seismic zone in the near future is high (Fig. 6). Scientists estimate that the probability of a magnitude 6 to 7 earthquake occurring in this seismic zone within the next 50 years is higher than 90%. Such an earthquake could hit the Mississippi Valley at any time. Recent simulations at the Missouri University of Science & Technology (Missouri S&T) suggests that a M6.5 quake emanating from the NMSZ would adversely impact structures sitting on fill, alluvium, and/or other unconsolidated materials more than 15 meters thick. Those structures most impacted would likely be taller buildings or towers, with fundamentals periods of vibration > 0.70 seconds. Embankments placed on unconsolidated alluvial materials, where fill + alluvium > 15 m thick. Structures more than eight stories high situated on old soil-filled basins greater than 25 to 35 m thick would also be subject to marked amplification of incoming seismic energy.

Some of the critical infrastructure that would likely be impacted by a M 6.5 quake at a distance of 210 to 240 km include: multiple span bridges (in particular, tail spans); buried oil, gas, coal slurry, water, and sewer pipelines crossing flood plains; high voltage (tall tower) transmission lines crossing flood plains; power plants situated along major river channels; water treatment and sewage treatment plants along channels; and underground storage tanks. Non-critical transportation infrastructure elements that would likely be affected include: barge traffic on navigable channels; fuel pumps made inoperative by loss of electricity; drainage ditch network in reclaimed flood plains; railroad corridors; interstate and secondary highway network; airport runways, and fuel handling facilities; and municipal off-stream water storage

Refined product service lines convey petroleum products between refineries and major metropolitan markets, from which these products are distributed. Significant disruption of the domestic refined product distribution lines has never occurred. The 'shock factor' of fuel unavailability would be unprecedented, necessitating rationing. Five of the six crude oil and natural gas pipelines crossing the Mississippi River could be compromised in a M. 6.5 earthquake emanating from the NMSZ (Fig. 7). Four of the nine largest natural gas trunk lines in the United States also cross the Mississippi River and could be expected to suffer considerable damage in a M. 6.5 quake. There are seven major pipelines crossing the Mississippi River in eastern St. Charles County, just north of St. Louis. All of these lines are buried in the loose unconsolidated sediments of the Missouri-Mississippi River flood plain most susceptible to liquefaction. Spillage of these lines would contaminate the municipal water supply for St. Louis.

The Bill Emerson Bridge across the Mississippi River in Cape Girardeau, MO is the only highway bridge south of St. Louis has been designed to resist earthquake ground motions. The newer highway bridges in St. Louis area, constructed since 1995, have also been designed for seismic loads. The I-64/US 40 double deck section in downtown St Louis was recently retrofitted for seismic loading. None of the railroad bridges have been designed or detailed for seismic loads.

Most fossil fuel and nuclear power plants are located on unconsolidated alluvium, including many along the Mississippi and Missouri Rivers. The impact of power generation loss depends on a number of factors, including the time of year an earthquake strikes. Biggest impacts would be on stalling disaster recovery, and some short term overloading of the surrounding transmission grid. Recovery time would be the single greatest impact on economic recovery of the region. The speed of recovery, ease of recovery, time span of recovery, and the public perception of recovery success all figure prominently in the various models examining the potential economic impact of a M>6 earthquake emanating from the NMSZ. In today's culture, the economic impact of being without electrical power is stupendous. Most homes and businesses cannot function for more than a few days without electricity. Businesses forced to relocate rarely return to their original pre-disaster locations, because of the cost. This problems was born out in the M6.9 Loma Prieta earthquake in 1989 and the M6.7 Northridge quake in 1994. These quakes saw a record number of business failures occur in their wake, and economic recovery did not occur for about 10 years.

Planning Aspects

State emergency management agencies need to identify critical facilities and components for disaster response on an unprecedented level, in regards to loss of transportation infrastructure, fuel pipelines, and electrical power. Some of the more vulnerable components of these systems include: cellular phone transmission towers; fiberoptic data transmission cables; insuring redundancy in electrical power grid; identifying alternate routes and fuel sources for emergency responders and alternate route packaging for commerce; realizing the limitations of temporary shelters; and employing sensor systems using GPS location fixed motes to provide monitoring feedback of transient conditions.

Unlike atmospheric events, such as hurricanes, earthquakes strike without warning. There is no evacuation ahead of the actual event. As a consequence, gasoline will be unavailable in areas without electrical power. Government agencies will not be able to count on sufficient aerial response assets, such as helicopters, to rescue stranded victims unless we know where they are located. We can expect that an earthquake will take down a fair number of the cellular repeater towers and that telephone transmission systems will be overtaxed. Text messaging and GPS receivers are rapidly emerging as the preferred method of hailing assistance in the wake of disasters, natural or man-caused. This is because text messaging does not require as much bandwidth as voice calls. Disaster victims are more likely to have a text message reach someone than a voice call.

GPS-equipped phones can also transmit user's location when calling 911, although this capability will likely be compromised cell towers will likely be compromised (iPhones employ triangulation between existing cell towers to fix their positions). However, victims may be able to text message coordinates or an interstate mile marker taken from phone or external GPS device, even if cell towers are down.

Everyone agrees that people have to be educated about what to do in specific scenarios. Extreme events, like combat, are always treacherous because most responders don't have first-hand experience with such catastrophes. Mass evacuations are difficult to plan for without recurring exercises and a through program of public education (this was born out in the response to the 1960 Chilean tsunami). Emergency managers will be lucky to get 2/3 of any populace to evacuate an area ahead of a natural disaster, if it is the first exposure to the natural peril. Those people with children more prone to leave than those without children.

Emergency responders should be provided with appropriate training to "expect the unexpectable;" which requires considerable innovation (e.g. San Francisco's loss of fire mains in the 1989 Loma Prieta quake). The most effective instruction is usually performed by responders who have personal experiences to share. Realistic training is most crucial aspect of preparedness (e.g. fire fighters practicing on real fires). Sending responders to other agency's disasters is probably our single best training option; there is no education like experience.

Regional and national economic impacts

A 1992 study by the National Research Council (NRC, 1992) estimated that a repeat of a M 7.5 to 7.7 event on the New Madrid Seismic Zone would cause upwards of $30 billion in damage. A more recent study has revised that estimate (MAE, 2008). Now an M 7.7 event on the southwest arm of the NMSZ would cause $200 million in hard damage to Memphis alone, and $50 to $70 billion in overall damage to the affected region. Comparisons between projected damages and actual damages are extremely complex, for many reasons, not the least of which is that fickle factor so aptly dubbed "public confidence."

It is difficult to estimate local, regional, and national disaster-driven economic impacts. The FEMA HAZUS software models cannot accurately gage many of the most important metrics, such as: infrastructure disruption impacts (as opposed to structural damage); trickle-down economic impacts, such as loss of confidence by consumers; people's reactions (e.g. people tend to hold onto their money after any sort of disaster, such as the 9/11 attacks); and the record number of retail business failures that usually result (e.g. 70% of the retail businesses in downtown New Orleans were lost in Hurricane Katrina in 2005).

Other "spin-off" and "spin-down" factors are very difficult to gage. In Hurricane Katrina, the government is implementing a plan to remunerate those people who lost their homes and personal property. This process, along with re-building, will likely take 3 to 10 years, or longer, to implement. Adjacent residents may not have lost their homes, but have lost their jobs/livelihood, the ability to sell their homes and relocate; and, difficulty getting homeowners insurance.

When raw materials or product stockpiles are suddenly or unexpectedly reduced/or their flow is constricted; the news media reports the potential shortages and all sorts of speculation ensues. This speculation can easily lead to inflated prices, which triggers consumer reaction, and, often leads to unforeseeable consequences, such as a drop in sales of SUVs while everyone waits to see what will happen to the price of gasoline at the pump. If spin-off and spin-down losses are tied to the most important factors influencing "public confidence" are television and print media coverage**.** Media coverage is ESSENTIAL to the success or failure of any emergency response scenario. Media tends to search out stories that elicit emotional responses or show graphic images to spike their viewing audience. Media market consultants recognize that viewers tend to select one channel over all others during any important event, often remaining loyal to that station thereafter (e.g. CNN in 1990-91 Gulf War; Fox News in 2003 Iraq invasion).

CONCLUSIONS

Based on historic activity and peleoseismic studies, the New Madrid Seismic Zone is overdue for triggering a Magnitude 6 earthquake (Tuttle et al., 2002). Quakes of up to M7 could also emanate from the Wabasha Valley Seismic Zone or the amorphous zone of seismic activity in South Central Illinois, although these are less probable (Street et al., 2004). An earthquake of M6.5 in the NMSZ could exert serious damage to densely populated urban areas of the Midwest, such as St. Louis, 220 to 300 km away from the NMSZ.

The most vulnerable components are petroleum product pipelines, highway and railway bridges, fiberoptic communications, tall structures, cellular repeater towers, electric transmission line towers, and power plants situated along major rivers. The loss of any or all of these infrastructure elements could severely impact these urban centers and serve to stall economic recovery of America's heartland, which lies at the center of vast transportation and commerce corridors.

A major complication with economic recovery will be the perception of public confidence about the recovery. The public receives virtually all of their information through mainstream media outlets. The media swiftly deployed their best correspondents into harm's way to report on conditions. Live streaming via satellite and video phone has changed viewer's expectations of being able to witness historic events when they occur. The media depends on cuing from: 1) government agencies and officials; 2) the public (via cell phones and e-mail); or, 3) from other media outlets (local affiliates, wire services, newspapers). They only tend to report what fails; not what remains standing.

Whether we like it or not, emergency responders are obliged to "court the media." The television media covers the "breaking news" as never before, and their stories are now posted Online, for everyone to view. Those stories can install public confidence or hinder it. We shouldn't forget that news networks are profit-making corporations operating in a highly competitive marketplace. Courting positive media coverage is not only an essential aspect of disaster response, it will be good for the nation's economy and benefit the recovery, more than most scientists or engineers realize.

REFERENCES

Anderson J. G., Lee, Y., Zeng, Y., Day, S., 1996, Control of Strong Motion by the Upper 30 Meters, Bulletin of the Seismological Society of America, Vol. 86, No. 6., pp. 1749-1759.

Bakun, W. H., and Hopper, M.G., 2004, Magnitudes and Locations of the 1811–1812 New Madrid, Missouri, and the 1886 Charleston, South Carolina, Earthquakes: Bulletin of the Seismological Society of America, v. 94:1 (February), pp. 64-75.

Bear, G. W., Rupp, J. A., and Rudman, A. J., 1997, Seismic interpretation of the deep structure of the Wabash Valley Fault System, Special issue on investigations of the Illinois basin earthquake region, Seismological Research Letters, Vol. 68 (4), 624-640.

Bolt, B.A., 2003, Earthquakes, 5th Ed: W. H. Freeman, New York.

Bristol, H. M., and Treworgy, J. D., 1979, The Wabash Valley fault system in southeastern Illinois, Illinois Institute of Natural Resources, Illinois State Geological Survey Division, Urbana, Illinois, Circular 509, pp. 20.

Chung, J.W., 2007, Development of a Geographic Information System-Based Virtual Geotechnical Database and Assessment of Liquefaction Potential for the St. Louis Metropolitan Area: Ph.D. dissertation in geological engineering, University of Missouri-Rolla.

Chung, J. W., and Rogers, J.D., 2009, Simplified Procedure for Spatial Evaluation of Liquefaction Potential for Regional Hazard Assessments; using the St. Louis Area, Journal of Geotechnical & Geoenvironmental Engineering, v. 135:11.

Cramer, C.H., 2001, The New Madrid Seismic Zone: capturing variability in seismic hazard analyses: Seismological Research Letters, 72, 664-672.

Fuller, M. L., 1912, The New Madrid Earthquake: U.S. Geological Survey Bulletin 494.

McBride, J. H., Sargent, M. L., and Potter, C. J., 1997, Investigating possible earthquake related structure beneath the southern Illinois basin from seismic reflection, Special issue on investigations of the Illinois basin earthquake region, Seismological Research Letters, Vol. 68 (4), 641-649.

Mid-America Earthquake Center (MAE), 2008, Impacts of Earthquakes on the Central USA: for the Federal Emergency Management Agency (FEMA), by the Mid-America Earthquake Center, University of Illinois.
Online: http://mae.ce.uiuc.edu/

National Research Council (NRC), 1992, The Economic Consequences of a Catastrophic Earthquake: Proceedings of a Forum. NRC Commission on Engineering and Technical Systems, National Academy Press, Washington, DC.

Nuttli, O. W., 1973, The Mississippi Valley earthquakes of 1811 and 1812: Intensities, ground motion and magnitudes, Bulletin of the Seismological Society of America, v. 63, no. 1, p. 227-248.

Nuttli, O. W., 1987, The effects of earthquakes in the central United States, Report for Central U.S. Earthquake Consortium, FEMA, Memphis, Tennessee, 33 pp.

Rogers, J.D., Karadeniz, D., and Chung, J.W., 2007, The Effect of Site Conditions on Amplification of Ground Motion in the St. Louis Area: Proceedings of the 4th International Conference on Earthquake Geotechnical Engineering, June 25-28, 2007, Thessaloniki, Greece, Paper No. 1768, 11 p.

Russ, D. P., 1982, Style and significance of surface deformation in the vicinity of New Madrid, Missouri, Investigations of the New Madrid, U.S. Geological Survey Professional Paper 1236, p. 95-114.

Spence, W., Herrmann, R.B., Johnston, A.C., and Reagor, G., 1993, Responses to Iben Browning's Prediction of a 1990 New Madrid, Missouri, Earthquake: U.S. Geological Survey Circular 1083.

Street R. L., Bauer, R. A., and Woolerly E. W., 2004, Short Note: Magnitude Scaling of Prehistorical Earthquakes in the Wabash Valley Seismic Zone of the Central United States, Seismological Research Letters, Vol. 75, n. 5, p. 637-641.

Tuttle, M. P., Schweig, E. S., Sims, J. D., Lafferty, R. H., Wolf, L. W., and Haynes M. L., 2002, The earthquake potential of the New Madrid Seismic Zone, Bulletin of the Seismological Society of America 92, 2080-2089.

FIGURES

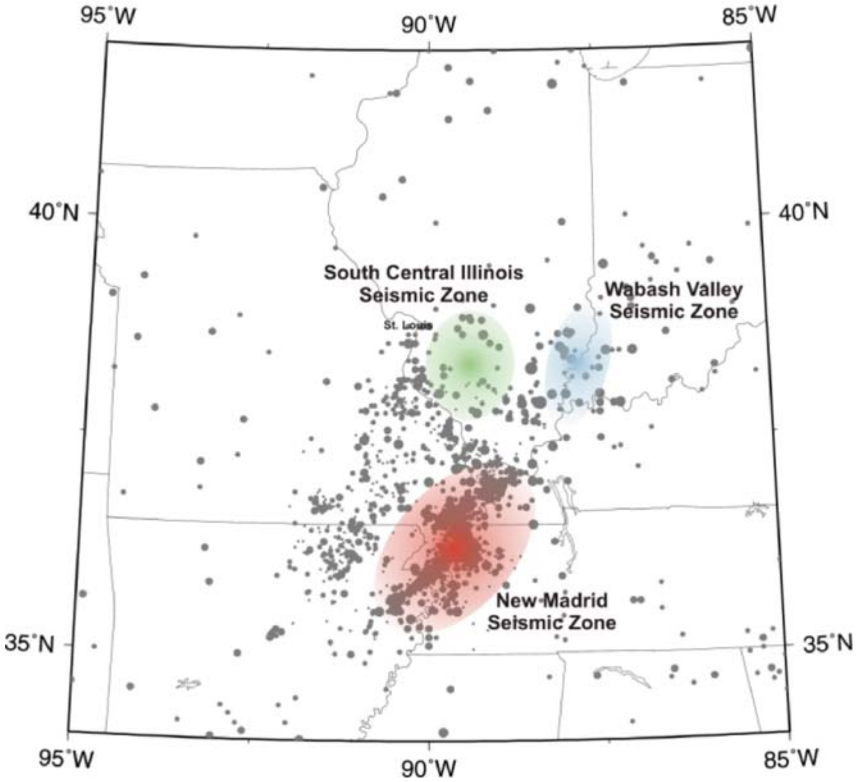

Fig. 1. Seismic source zones in the central United States. South Central Illinois is an area of diffuse seismicity which is not well documented or yet understood, because it is covered by glacial outwash.

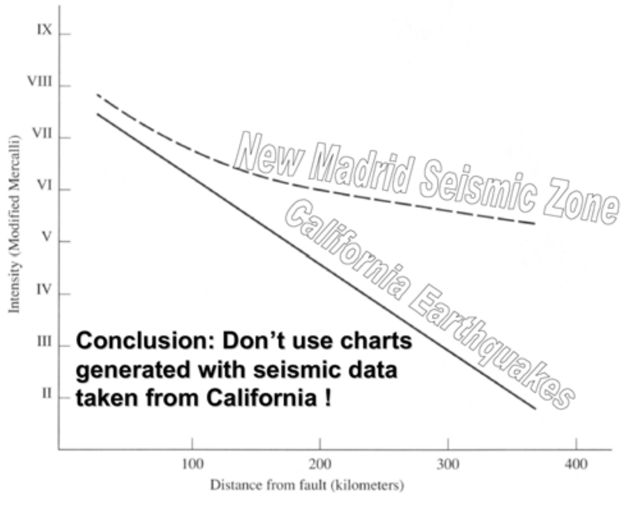

Fig. 2. Contrast between damping of shaking intensity with distance from seismic sources in California and the Midwestern US (taken from Bolt, 2003). Most damping models prior to 2000 were biased by data from California earthquakes.

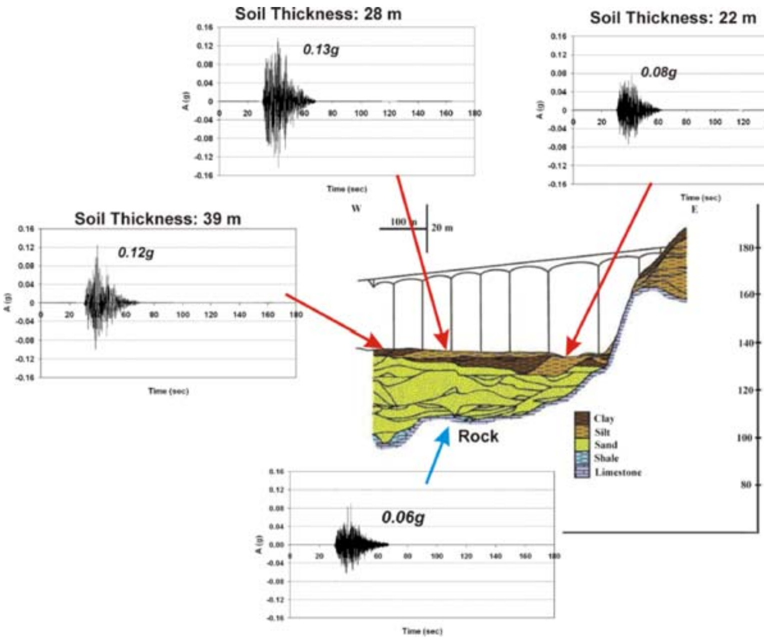

Fig 3. Effect of soil thickness on peak ground acceleration from a Magnitude 6.8 earthquake striking the Creve Cour Bridge on the southern bank of the Missouri River about 110 km from a quake centered in south central Illinois.

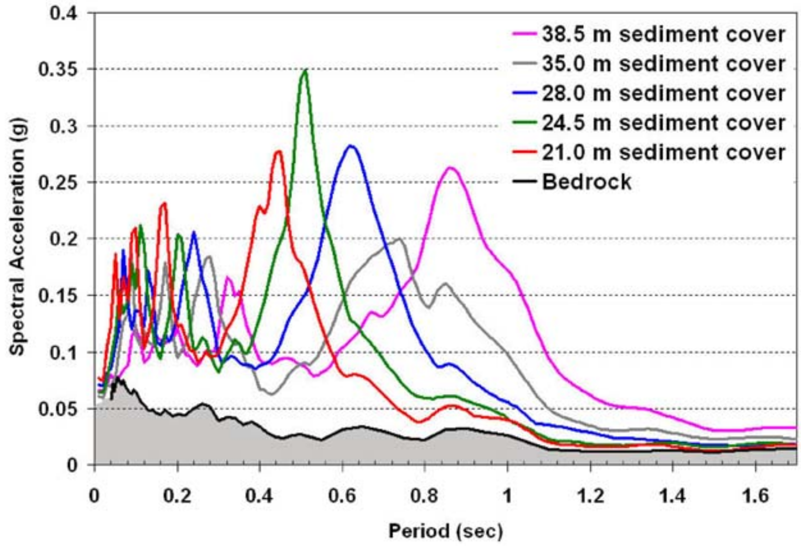

Fig 4. Variation in expected spectral acceleration with alluvial thickness in the St Louis, MO area

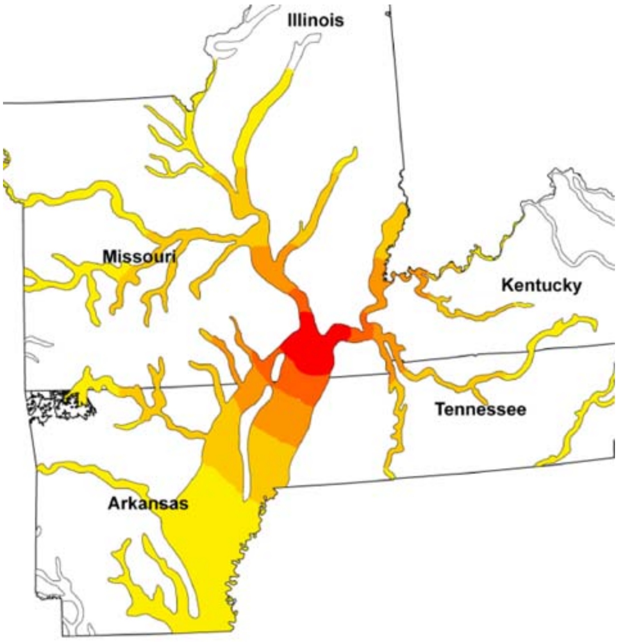

Fig. 5. The earthquake hazard maps of the Midwestern US will likely look something like this; highlighting those areas underlain by unconsolidated alluvium, along major river channels. The intensity of shaking will depend on the earthquake epicenter. In this case, a quake emanating from the northern end of the New Madrid Seismic Zone has been assumed.

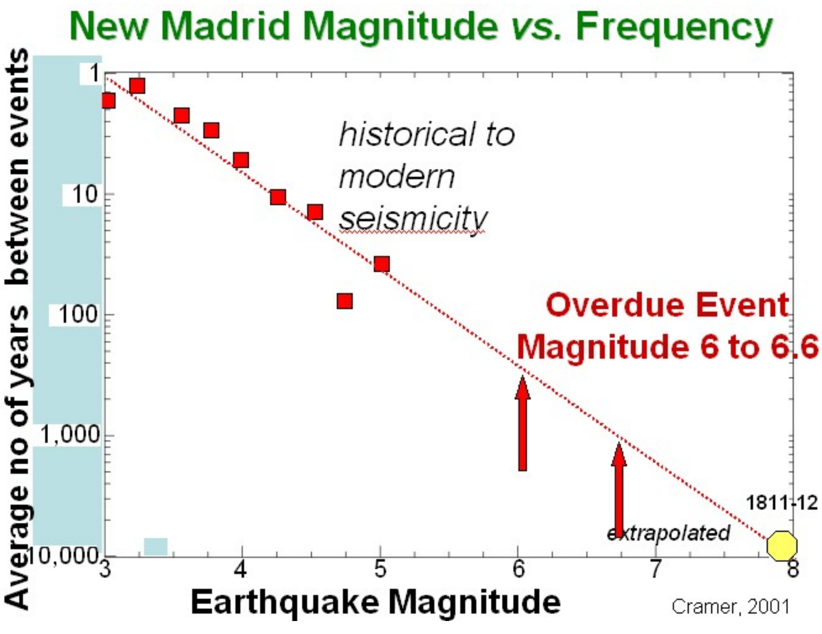

Fig. 6. Plot comparing earthquake magnitude and frequency for the New Madrid Seismic Zone, modified from Cramer (2001). The most likely destructive earthquake is an M 6 to 6.6 event, which is believed to have a recurrence frequency of once every 70+/- 15 years. The last M6+ quake occurred in 1895.

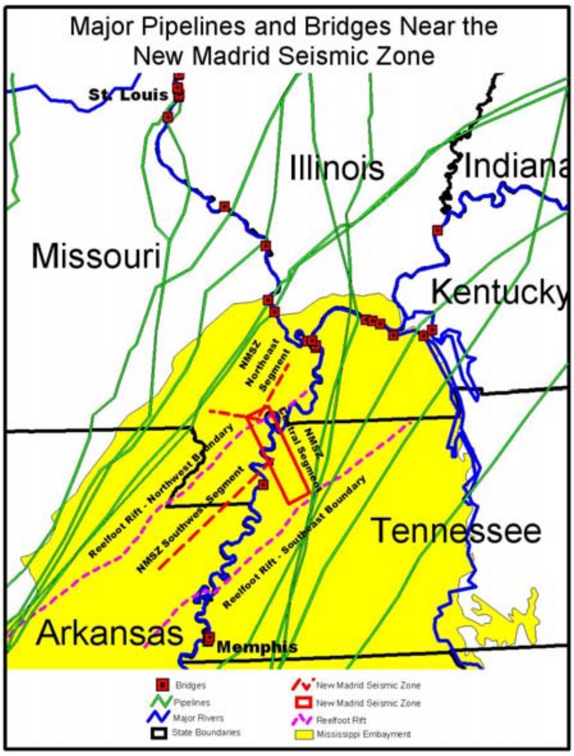

Fig. 7. Major pipelines (in green) and highway bridges (red squares) in the New Madrid Seismic Zone, compiled by David Hoffman at Missouri S&T. The faults are shown as dashed red lines, while the approximate limits of the underlying Reelfoot Rift are delineated by dashed pink lines.