Final Technical Report
Mid-America ShakeMap: a Large Regional Implementation

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Report prepared by Thomas B. Brackman and Mitchell M. Withers.

ABSTRACT

ShakeMap is a tool using basic seismological concepts for the rapid generation of maps of various presentation of ground motion and shaking intensity following significant earthquakes and is based on both observed and modeled data. We implemented ShakeMap for the Mid-American region of the Advance National Seismic System (ANSS-MA) using the default amplification procedure of ShakeMap (e.g. Brackman and Withers, 2006) and data from the Map of Surficial Deposits and Materials in the Eastern and Central United States (Fullerton et. al., 2004). The results were compared with Community Internet Intensity Maps (CIIM) (Wald 1999a). The description of soils (Fullerton et. al., 2004) was used to discriminate units according to the soil profile type classification for seismic amplification (FEMA, 1994). A grid with a spacing of 0.0152 degrees between points was used to determine a shear wave velocity for import into ShakeMap. Scenarios were compared to CIIM of each event. The instrumental intensity regression of Kaka and Atkinson (2005) is currently used as the default regression for the study area. The newer regression of Atkinson and Kaka (2007) seems to fit the data better and should be tested further.

Introduction

Immediately after a significant earthquake emergency managers must rapidly assess damage and find answers to many important questions: Where is the worst damage?

Where is the least damage? What equipment and personnel must be mobilized and in what amount? ShakeMap was developed by the U.S. Geological Survey Earthquake Hazards Program in cooperation with regional seismic network operators to supply the needed answers for questions regarding coordinating and managing response efforts by producing near-real-time maps of ground motion and shaking intensity following significant earthquakes (Wald et. al., 2004). ShakeMap was implemented in the Upper Mississippi Embayment of the central and eastern United States (figure 1) in the New Madrid area (Brackman, 2005) and is currently in operation (http://folkworm.ceri.memphis.edu/shakemap).

In order to provide greater area of coverage we implemented ShakeMap for the Mid-America region of the Advanced National Seismic System (ANSS-MA) (figure 2). The primary impediment was creation of a suitable grid with associated amplification factors. Attenuation and intensity relations are also important second order considerations. We took advantage of the surficial geologic information within the community and gathered information from various private and government sources to form an amplification grid for the ANSS-MA region and configured and implemented a second instance of the software at CERI that incorporates all broadband and strongmotion channels that are currently being processing (includes all real-time stations from all USGS funded networks). Results are heavily modeled due to the relative lack of station density throughout most of the region. However, with proper interpretation and presentation of errors forthcoming from the ShakeMap community, we believe that this implementation provides an invaluable resource to the community.

Grid and Amplification Factors

It well documented that variations in soil types (near-surface geologic materials) can cause spatial differences in damage due to shaking (e.g. Tinsley and Fumal, 1985; EPRI, 1993; Toro, 2001). These differences can be quantified and are used by ShakeMap in the form of amplification factors determined by using a reference velocity, a predetermined mean shear wave velocity for the top 30 meters (Vs30) and the slope of a linear regression of plotted field data from Borcherdt (1994). The amplification factors are assigned to points on a grid of configurable spacing (approximately 0.0152 degrees for this implementation) and are applied after modeling constrained by instrumental seismic data (Wald et. al., 2004). Using the default amplification procedure of ShakeMap (e.g. Brackman, 2005) and data from the Map of Surficial Deposits and Materials in the Eastern and Central United States (Fullerton et. al., 2004) it was a straightforward process to duplicate the amplification procedures for the ANSS-MA.

The surficial geologic map of the Eastern and Central United States depicts the distribution of surficial geologic deposits and other materials (figure 2). The map was derived from published maps in the U.S. Geological Survey's Quaternary Geologic Atlas of the United States map series (U.S. Geological Survey Miscellaneous Investigations Series I–1420). It was compiled at 1:1,000,000 scale, to be viewed as a digital map at 1:2,000,000 nominal scale and to be printed as a conventional paper map at 1:2,500,000 scale (Fullerton et. al., 2004). The surficial geologic map provides a broad overview of the distribution of more than 150 types of surficial deposits and materials, as recognized in engineering geology (Fullerton et. al., 2004). Our work here concentrated on particle size or texture and thickness to bedrock.

The particle size or texture description of the soils in the surficial geologic map (Fullerton et. al., 2004) was used to classify each individual unit according to the soil profile type classification for seismic amplification (FEMA, 1994) (table 1). The soils were binned into the categories: A) hard rock, B) rock, C) hard and/or stiff/very stiff soils, and most gravels, and D) sands, silts and/or stiff/very stiff clays, some gravels. The average shear wave velocity in meters/second (m/s) associated with each category was then assigned to that unit. The average shear wave velocity, an assumed bedrock velocity of 1130 m/s and the average unit thickness was used to compute the average shear wave velocity to 30 meters. In areas where the soils were greater than 30 meters the average shear wave velocity associated with each description was used. In areas where the soils were less than 30 meters the soil average and the bedrock average velocity were averaged over 30 meters. Averaging was done by determining the "slowness" of the soil and bedrock over their respective thicknesses. The slowness was inverted to obtain velocity.

A grid of points from -102.0000 longitude, 49.9848 latitude to -75.0392 longitude, 24.0367 latitude with a spacing of 0.0152 degrees, was constructed and overlaid on the modified Map of Surficial Deposits and Materials in the Eastern and Central United States (figure 3) to determine a shear wave velocity to 30 meters for each point. These data points were imported into ShakeMap and tested.

The Amplification factors determined using the default ShakeMap protocols for the study area is shown in table 2. The 0.1 – 0.5 second amplification factors were applied to scale peak ground acceleration while the 0.4 – 2.0 amplification factors were used to scale peak ground velocity.

Instrumental Intensity

Numerous attempts have been made to associate peak ground motions with Modified Mercalli Intensity (MMI) (e.g. Trifunac and Brady, 1975). The traditional use of this regression is to determine peak ground motions from historic earthquake observations. ShakeMap uses the regression to map recorded and modeled peak ground motions to MMI. The intensity determination is based on instrumental data, not observed reports, thus the designation of instrumental intensity. Instrumental Intensity maps were created to quickly and easily disseminate information regarding the intensity of shaking after an earthquake. Wald et al., (1999a) developed the instrumental intensity regression, for use by ShakeMap, specifically for the Western United States. Kaka and Atkinson (2004) developed an instrumental intensity regression for the southeast area of Canada. Recently Atkinson and Kaka (2007) developed an empirical relationship for North America with regional corrections based on magnitude and distance.

In order for ShakeMap to correctly represent instrumental intensity in the Mississippi Embayment, the regression developed by Wald et al., (1999a), was initially replaced with Kaka and Atkinson (2004). We used the newest relationship of Atkinson and Kaka (2007) to develop a preliminary instrumental intensity regression. The ShakeMap module uses the simple uncorrected form of the equation.

Accuracy of the instrumental intensity maps was tested by comparing the instrumental intensity regressions of Atkinson and Kaka (2007), Kaka and Atkinson (2004) and Wald

et al., (1999a) to the Community Internet Intensity Maps (CIIM) (Wald et al., 1999b) from the M 4.6 Fort Payne (figure 4) and the M 5.2 1980 Sharpsburg, KY earthquakes (figure 5). The regression of Wald *et. al*., (1999a) under predicts MMI values in the near-field and drastically under predicts in the far-field, while the instrumental intensity map using Kaka and Atkinson (2004) over predicts for both events. The newer regression of Atkinson and Kaka (2005) predicts less than Kaka and Atkinson and more than Wald (1999a). The new regression does not over predict as much as Kaka and Atkinson (2004) which is more in line with the Modified Mercalli Intensities of the CIIM for the same event. Instrumental intensities taken from a line of latitude through the epicenter of the earthquake show the instrumental intensities quantitatively.

Attenuation Relationship

ShakeMap mimics a dense array of seismometers by using an attenuation relationship to model peak ground motions at virtual or "Phantom" stations between existing seismic stations (Wald et al., 1999). It is well established that attenuation in the central and eastern United States is inherently different than that in the Western United States (e.g. Boore and Atkinson, 1987; Toro and McGuire, 1987; Boore and Joyner, 1991; EPRI, 1993; Toro et al., 1997; Atkinson and Boore, 1997; Frankel et. al., 1996; Somerville et. al., 2001 and Campbell, 2001; EPRI 2004; Kaka and Atkinson, 2005).

In order to implement a well-established, consensus-based baseline attenuation relationship, it would be prudent to incorporate multiple weighted attenuation relations into ShakeMap in agreement with the CEUS Portion of Draft Versions of the 2002 Update of the National Seismic Hazards Maps (Frankel, 2002). However, until such time as software improvements are available, we instead use a single relationship that is most compatible with our needs and available data.

No new work was done to update the attenuation relationship; however, it is difficult to deaggregate amplification, attenuation, and conversion to intensity. It is difficult to determine if the differences are from instrumental intensity regression predicting incorrectly or from attenuation relationships predicting incorrectly. An attenuation relationship study for the Mississippi Embayment, similar to that performed by Kaka and Atkinson (2005) needs to be conducted. However, further testing and refinement of the model, based on future recorded earthquakes, is warranted and recommended.

Conclusion

Using the default amplification procedure of ShakeMap (e.g. Brackman, 2005) and data from the Map of Surficial Deposits and Materials in the Eastern and Central United States (Fullerton et. al., 2004) it was a straightforward process to duplicate ShakeMap amplification procedures for the Mid-America region of the ANSS. The results compare favorably with the Community Internet Intensity Map for the same event. The shear wave velocities assigned to each unit should be checked with actual measurements of VS30. Shear wave velocity measurements conducted by engineering firms as a requirement of newly adopted building codes would help to determine the accuracy of the classification. Bedrock velocities should be corrected to include the variability of the subsurface. As they occur, ShakeMap output should be compared to the CIIM to confirm the accuracy of the regression. The particle size or texture description of the soils in the surficial geologic map (Fullerton et. al., 2004) was used to classify each individual unit according to the

soil profile type classification for seismic amplification (FEMA, 1994). A grid of points with a spacing of 0.0152 degrees was used to determine a shear wave velocity for import into ShakeMap. Scenarios were compared favorably to the CIIM for each event.

The instrumental intensity regression of Kaka and Atkinson (2005) is currently used as the default regression for the study area. The newer regression of Atkinson and Kaka (2007) seems to fit the data better and should be tested further.

The grid spacing of the amplification points should be reduced to ensure proper map depiction while not increasing map generation time. Basin resonance was not included in the determination of shaking intensity, but should be examined, as well as the effects of de-amplification from loose soils. Finally, the density of stations needs to be improved. There are only 40 real-time strongmotion stations in the Mid-America region of the ANSS. The greatest concentration of stations is the ten freefield and reference sites in the Memphis metropolitan area. While this project focused on modeling, the accuracy of ShakeMap depends on near-real-time data from a large number of on-scale, high quality seismographs.

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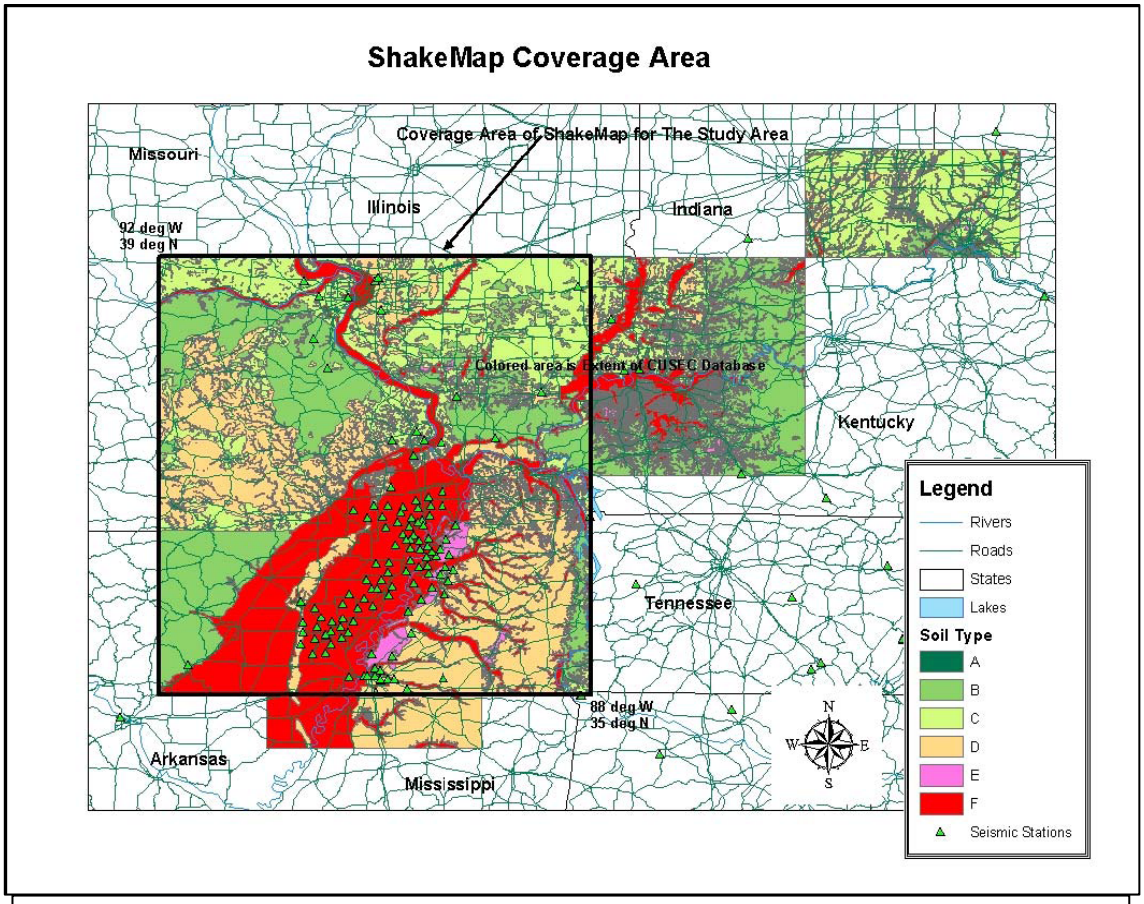


Figure 1. Coverage area of ShakeMap Prior to this study. Area inside of rectangular box bounded by 92° West, 39° North, 88° West and 33° North.

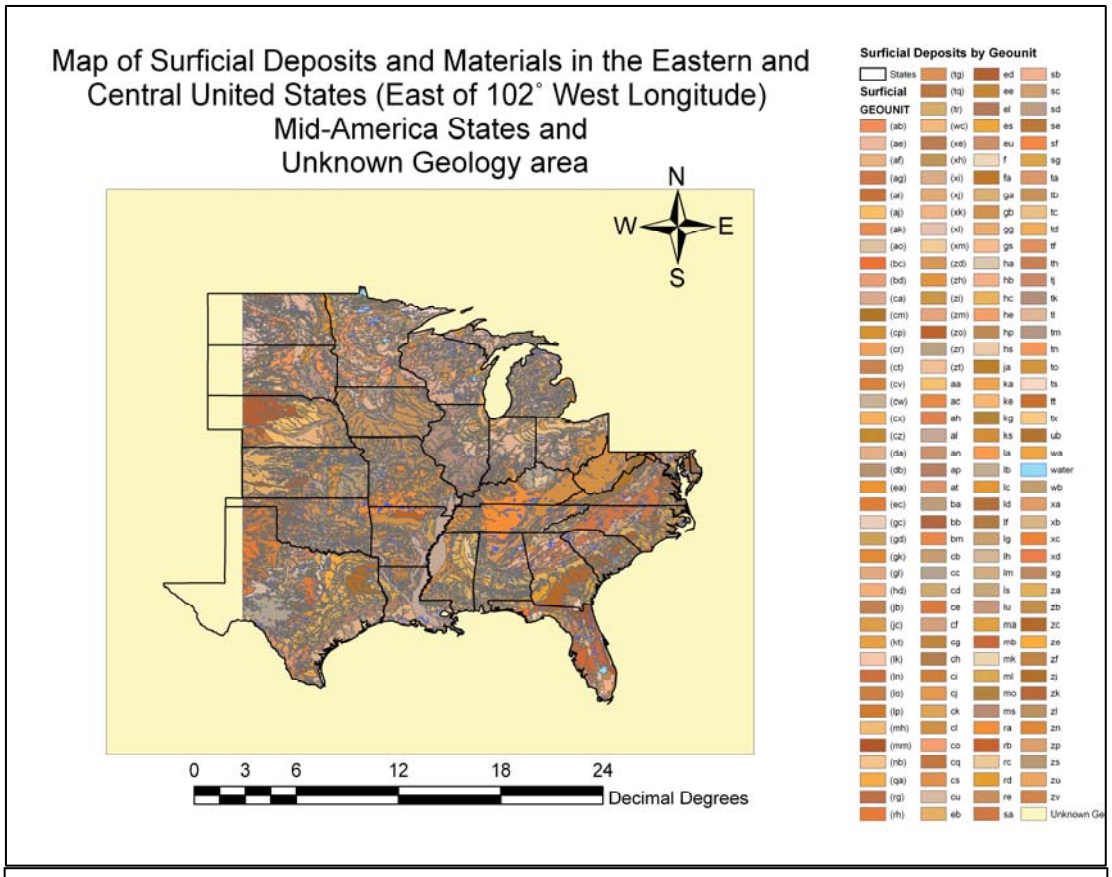


Figure 2. Coverage area of ShakeMap implementation for the Mid-America region of the Advance National Seismic Network (ANSS-MA). Map of Surficial Deposits and Materials in the Eastern and Central United States (Fullerton et. al., 2004) used in creation of Amplification factors.

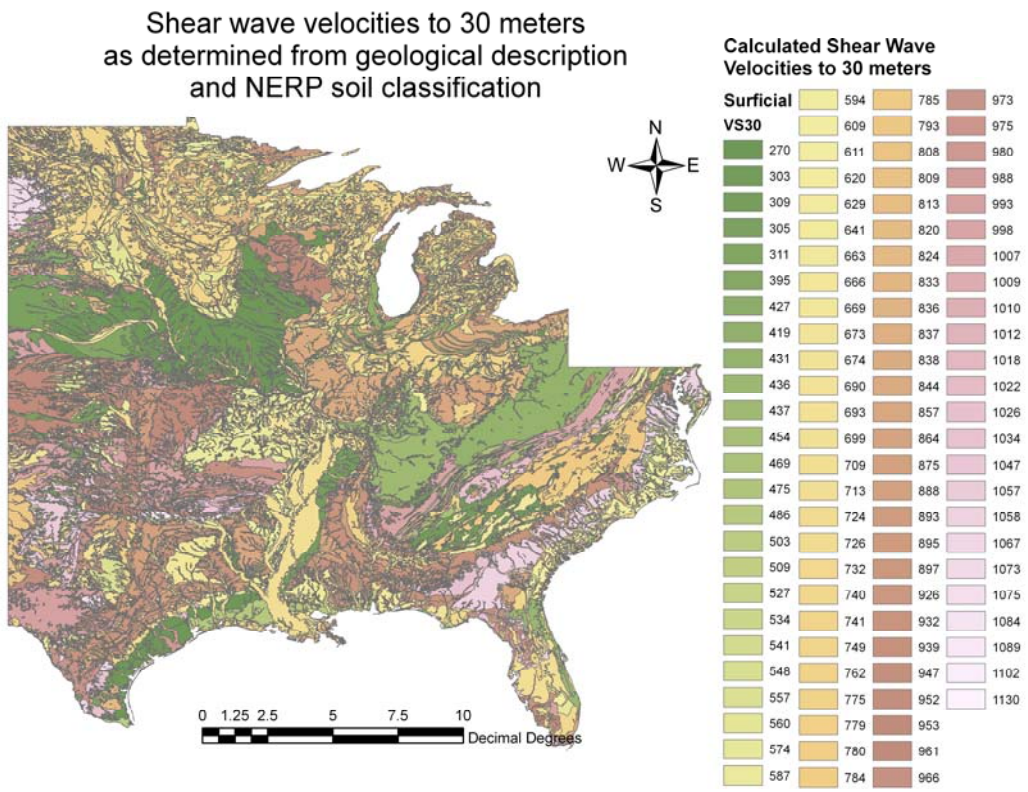
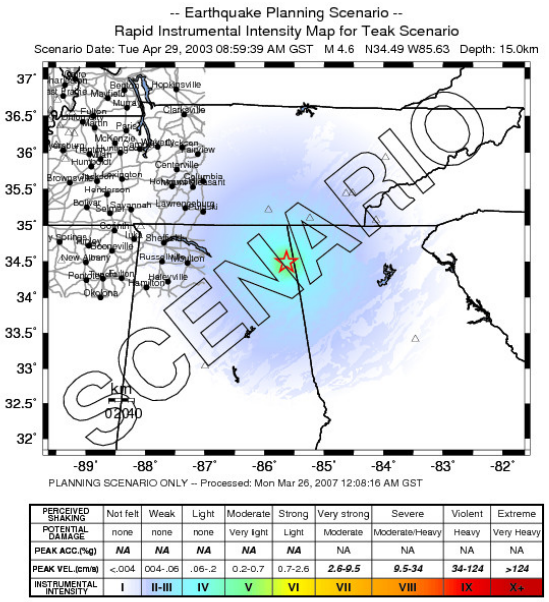
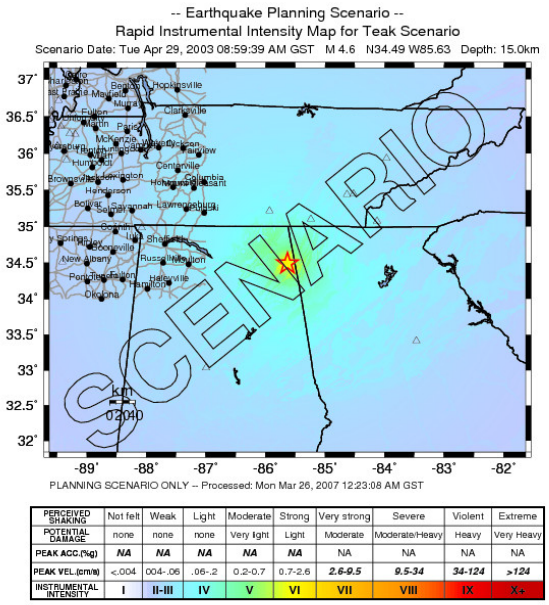


Figure 3. Modified Map of Surficial Deposits and Materials in the Eastern and Central United States (Fullerton et. al., 2004). Map depicts shear wave velocity to 30 meters (m/s) assigned to each geounit inferred from soil descriptions and average thicknesses. A grid of points from -102.0000 longitude, 49.9848 latitude to -75.0392 longitude, 24.0367 latitude with a spacing of 0.0152 degrees, was constructed and overlaid on the map to determine a VS30 for each point. These data points were imported into ShakeMap.



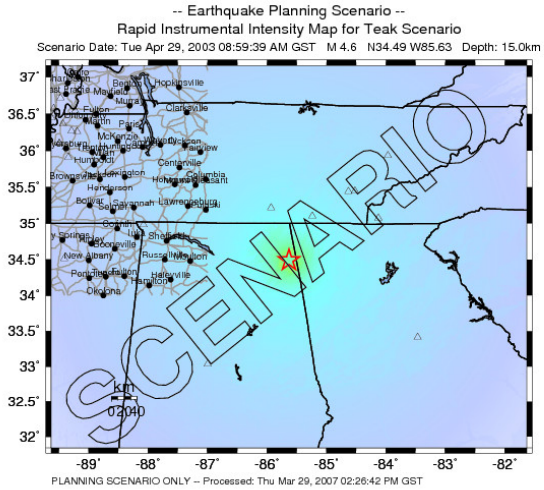
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	NA	NA	NA	NA	NA	NA	NA	NA	NA
PEAK VEL.(cm/s)	<.004	.004-.06	.06-.2	0.2-0.7	0.7-2.6	2.6-9.5	9.5-34	34-124	>124
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

a) Wald et al., (1999a)



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	NA	NA	NA	NA	NA	NA	NA	NA	NA
PEAK VEL.(cm/s)	<.004	.004-.06	.06-.2	0.2-0.7	0.7-2.6	2.6-9.5	9.5-34	34-124	>124
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

b) Kaka and Atkinson (2004)



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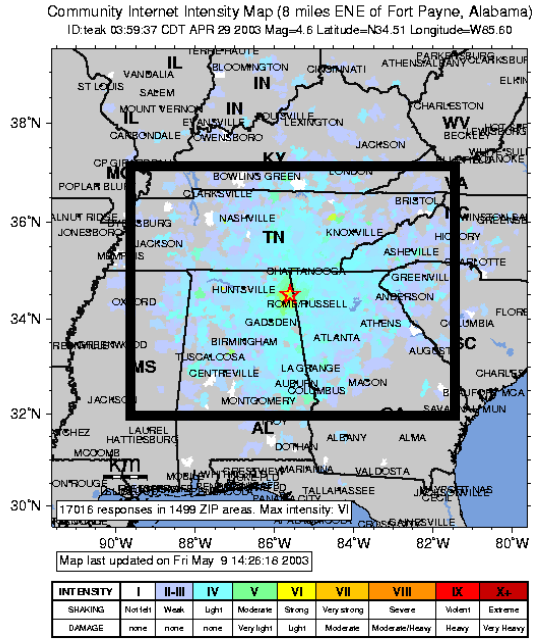
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

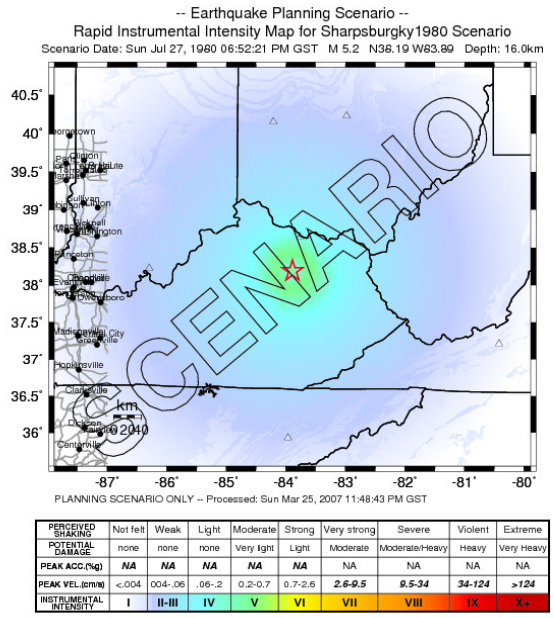
c) Atkinson and Kaka (2007)



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy

d) Community Internet Intensity Maps (CIIM) (Wald et al., 1999b)

Figure 4. Scenario of the earthquake, teak, 8 miles ENE of Fort Payne, AL, 08:59:39 UTC, April 29, 2003, Mag. 4.6, Latitude N, 34.51 Longitude W85.60.
(http://neic.usgs.gov/neis/eq_depot/2003/eq_030429/) .
Each map depicts the use of different instrumental intensity regressions: a) Wald et al., (1999a), b) Kaka and Atkinson (2004), c) Atkinson and Kaka (2007) as compared to d) Community Internet Intensity Maps (CIIM) (Wald et al., 1999b). Outline of box in d) is extent of scenario maps. The regression of Atkinson and Kaka (2007) is in better agreement with the CIIM than those of Wald et al., (1999a) and Kaka and Atkinson (2004).



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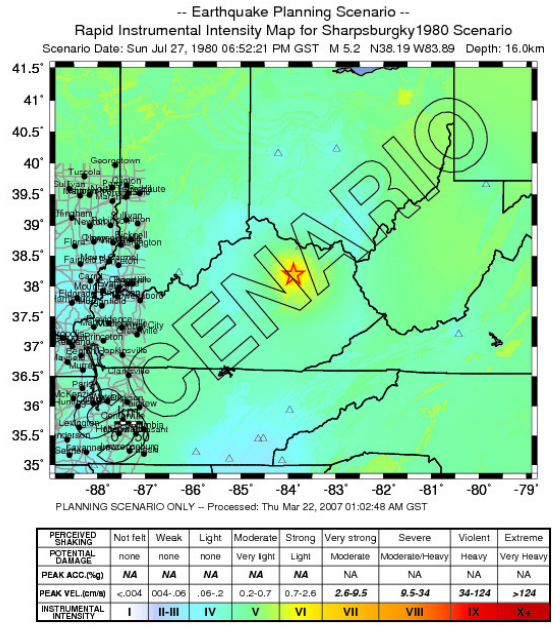

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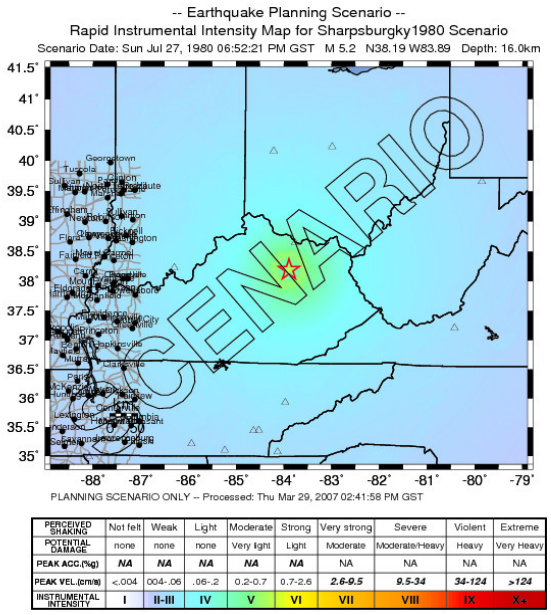

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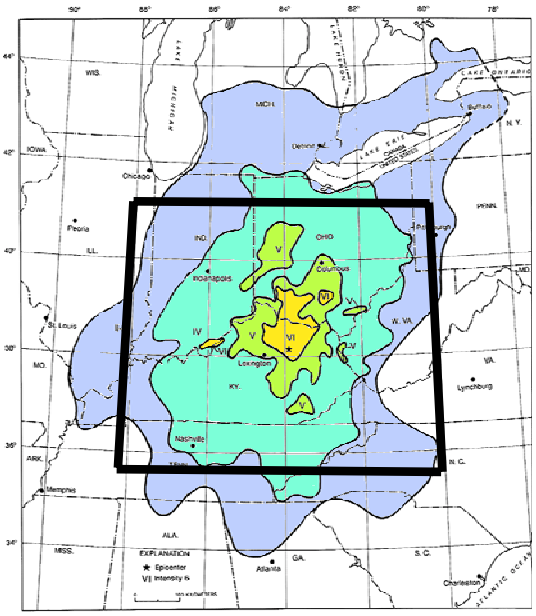

d) Isoseismal maps based on intensity estimates from data. (Stover and Coffman 1993)

Figure 5. Scenario of the historic Sharpsburg, KY earthquake, Northeast Kentucky, near Sharpsburg, Bath County 1980 07 27 18:52:21.4 UTC Magnitude 5.1 Intensity VII (http://earthquake.usgs.gov/regional/states/events/1980_07_27.php)
Each map depicts the use of different instrumental intensity regressions: a) Wald et al., (1999a), b) Kaka and Atkinson (2004), c) Atkinson and Kaka (2007) as compared to d) Isoseismal maps based on intensity estimates from data. (Stover and Coffman 1993). Outline of box in d) is extent of scenario maps. The regression of Atkinson and Kaka (2007) is in better agreement with the isoseismal maps than those of Wald et al., (1999a) and Kaka and Atkinson (2004).

Table 1.
Soil profile type classification for seismic amplification (FEMA, 1994).

Soil Type	General Description	Avg. Shear Wave Velocity (feet/s)	Avg. Shear Wave Velocity (m/s)	Avg. Blow Counts	Avg. Shear Strength (lbs/sq.ft.)
A	Hard Rock	> 5,000	> 1,500		
B	Rock	2,500 - 5,000	760 - 1,500		
C	Hard and/or stiff/very stiff soils; most gravels	1,200 - 2,500	360 - 760	> 50	2,000
D	Sands, silts and/or stiff/very stiff clays, some gravels	600 – 1,200	180 - 360	15 - 50	1,000 - 2,000
E	Small to moderate thickness (10 to 50 feet) soft to medium stiff clay, Plasticity Index > 20, water content > 40 percent	< 600	< 180	< 15	< 1,000
E_2	Large thickness (50 to 120 feet) soft to medium stiff clay Plasticity Index > 20, water content > 40 percent	< 600	< 180	< 15	< 1000
F_1	Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils.	By definition the F classification requires that a site dependent evaluation of the engineering parameters be conducted, as they do not fall into any of the other soil classifications.			
F_2	Peats and/or highly organic clays greater than 10 feet thick				
F_3	Very high plasticity clays greater than 25 feet thick with Plasticity Index > 75				
F_4	Very thick soft/medium stiff clays greater than 120 feet thick				

Table 2
Amplification Factors for Mississippi Embayment Based on NEHRP soil Classification.
With Soil Type B as Reference Velocity.

		Input Rock Peak Ground Acceleration (%g)			
Soil type (ave.vel.)	Period (s)	< 15%	15 - 25%	25 - 35%	> 35%
B (1130 m/s)	0.1 - 0.5	1	1	1	1
	0.4 - 2.0	1	1	1	1
C (560 m/s)	0.1 - 0.5	1.3	1.2	1.1	1.0
	0.4 - 2.0	1.6	1.5	1.5	1.4
D (270 m/s)	0.1 - 0.5	1.7	1.4	1.2	0.9
	0.4 - 2.0	2.5	2.4	2.1	1.9
E (180 m/s)	0.1 - 0.5	1.9	1.6	1.2	0.9