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Shakemap for Memphis
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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 types of ground motion and shaking intensity following significant earthquakes and is based on both observed and modeled data. We adapted the amplification factors, attenuation relationship, and instrumental intensity correlation to be more appropriate for ShakeMap operational requirements in eastern North America (specifically, the Upper Mississippi Embayment) and compared the results to recorded and historic seismic events. The attenuation relationships of Kaka and Atkinson (2005) and Toro et al. (1997) were used for magnitudes less than and greater than six, respectively. Kaka and Atkinson, (2004) was used as the instrumental intensity regression. The amplification protocol of Borcherdt, (1994) applied to data from Bauer (2001) is adequate for the implementation of ShakeMap in the Mississippi Embayment.

Introduction

Immediately after a damaging 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).

The area for implementation is located in the Upper Mississippi Embayment of the central and eastern United States and is centered on the New Madrid seismic zone (fig. 1). The area covers a four by four degree grid from 92° W to 88° W and 35° N to 39° N and encompasses 6 states and the major metropolitan areas of Memphis, TN and Saint Louis, MO. ShakeMap uses a ground motion prediction equation/relationship (attenuation relation), soil amplification factors and peak ground motion correlated to Modified Mercalli intensity (instrumental intensity) to determine the output parameters for creation of the maps. Because of large-scale regional variations, parameters need to be determined for each specific region where ShakeMap is put into operation.

Amplification Factors

It has been demonstrated 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 (presently approximately 1.7km) 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 the data from Bauer et. al., (2001) it was a straightforward process to duplicate the amplification procedures for the Mississippi Embayment.

The NEHRP soil classification scheme (Table 1) used by Bauer et. al., (2001) is comparable to the soil classification descriptions of Borcherdt (1994) (Table 2). Thus Borcherdt's (1994) amplification curves will transfer to the central and Eastern United States. The CUSEC map soil type designation of "F" pertained to liquefiable soils; ShakeMap made no distinction for these soil types. In order to work around this problem the "F" designation was assigned an "E" designation.

The Amplification factors determined using the default ShakeMap protocols, for use by ShakeMap for the study area are shown in table 3. The 0.1 – 0.5 second amplification factors are applied to scale peak ground acceleration while the 0.4 – 2.0 amplification factors were used to scale peak ground velocity.

An improvement to the amplification procedures would be to incorporate the effects of the entire soil column. Cramer (2004) developed an approach that uses the entire soil column. The transition from Borcherdt (1994) to Cramer (2004) would be possible. However, it may require major software changes, backward compatibility issues and would be less manageable. This is an area that should be examined in detail, but a quick assessment made the adaptations look feasible for the essentially flat basins of the Mississippi Embayment. However, in basins of varying depth, using the entire soil column would not necessarily be feasible. For the time being the Vs30 scheme of Borcherdt (1994) is quite sufficient and should be left in place.

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. A comparison of various regressions (fig. 2) shows a sharp contrast from the western United States to the central and eastern United States. In order for ShakeMap to correctly represent instrumental intensity in the Mississippi Embayment, the regression developed by Wald et al., (1999a), was replaced with Kaka and Atkinson (2004) developed specifically for the central and eastern United States.

Accuracy of the instrumental intensity maps was tested (Brackman, 2005) by comparing the instrumental intensity regressions of Kaka and Atkinson (2004) and Wald et al., (1999a) to the regional earthquakes of **M** 4.2, Blytheville, Arkansas April 29, 2003 (not shown) and **M** 4.1, Blytheville, Arkansas February 10, 2005 (NM722) (fig. 3) and historic events **M** 8.1, Dec. 16, 1811 (Johnston and Schweig, 1996) (fig. 4) and the **M** 6.6, Charleston, Missouri 1895 (Stover and Coffman, 1993) (not shown).

The regression of Wald *et. al*., (1999a) showed an under prediction of MMI values in the near-field and a drastic under prediction in the far-field, while the instrumental intensity map using Kaka and Atkinson (2004) only slightly over predicted for both recorded and historic events. The regression of Wald *et.*

al., (1999a) clearly under estimated the intensity associated with earthquake shaking. Analysis of the results suggests that the accuracy of Kaka and Atkinson (2004) is reasonably acceptable.

Results for earthquakes of magnitudes greater than five depended heavily on the accuracy of the attenuation relationship used and the accuracy of the historic felt reports. New Madrid and Charleston events were close enough for emergency response personnel to know where the most intense damage had occurred and the approximate extent of damage. In order to accurately assess the instrumental intensity regressions at higher magnitudes, further testing and refinement of the model, based on future recorded earthquakes, is warranted and recommended.

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.

Kaka and Atkinson (2005) used data from central and eastern United States empirical databases and modeled data from Atkinson and Boore (1995). Therefore, the equation obtained is typically based on recorded ground motions of magnitudes less than five. Kaka and Atkinson, (2005) state that the relationship might under estimate peak ground motions for magnitudes equal to or greater than six, therefore, limiting the range to lower magnitudes is prudent.

The attenuation relationships of Toro et. al., (1997) and Atkinson and Boore (1995), were tested for accuracy using the instrumental intensity regression of Kaka and Atkinson (2004) and Borcherdt's (1994) amplification protocol. Scenarios were constructed and the results compared to historic Modified Mercalli Intensity (MMI) maps of the 1895 Charleston, Missouri M 6.6 event (Stover and Coffman, 1993) and Dec. 16, 1811 (D1) M 8.1 New Madrid 1811 event (Johnston and Schweig, 1996). The attenuation relationship of Kaka and Atkinson, (2005) was tested (Brackman, 2005) by comparing to the Community Internet Intensity Maps of the regional earthquakes of **M** 4.2, Blytheville, Arkansas April 29, 2003 (hwb0430a) and **M** 4.1, Blytheville, Arkansas February 10, 2005 (NM722)

Inspection of the NM722 (fig. 5) event showed the attenuation relationship of Kaka and Atkinson (2005) to be in fair agreement with the Community Internet Intensity Maps of both earthquakes and was over predicting by only a small amount. An examination of the far field showed an over prediction of intensities.

Comparison of a magnitude 7.4 scenario to isoseismals of the 1811-1812 New Madrid Sequence (fig. 6) (Johnston and Schweig, 1996) showed that the relation of Atkinson and Boore, (1995) drastically under estimates the shaking intensity in the near source. Toro et. al., (1997) also seemed to be underestimating in the near source. The lack of widespread amplification factors limited the area of investigation and thus the far field could not be accurately assessed.

While it is difficult to deaggregate amplification, attenuation, and conversion to intensity, the differences could be from instrumental intensity regression predicting incorrectly. Kaka and Atkinson (2005) states that regressions are generally non-transferable from region to region. An instrumental intensity regression using local data will be initiated in the summer of 2005 for the Mississippi Embayment by Atkinson (personal communication). The study could verify the validity of the instrumental intensity regression. If the regressions are found to be similar, then the over prediction could be in the attenuation relationship. An attenuation relationship study for the Mississippi Embayment, similar to that performed by Kaka and Atkinson (2005), will then need to be conducted. However, further testing and refinement of the model, based on future recorded earthquakes, is warranted and recommended.

The relationship of Toro et. al., (1997) is a better predictor for an event on the order of the 1811 event, while the relationship of Atkinson and Boore (1995) may be a better predictor for the Charleston, Missouri, type events. It is possible that the prediction of peak ground motions by the attenuation relationships for the New Madrid and Charleston events are close enough for emergency response personnel to know where the most intense damage has occurred and the approximate extent of damage. The empirical relationship of Kaka and Atkinson (2005) should be used to predict peak ground motions for magnitudes at and below six. Assuming it is prudent to err on the side of caution and include a factor of safety, the higher estimates of peak ground motion by the relationship of Toro et. al., (1997) should be used for earthquakes of magnitude six and larger.

Conclusion

For the Upper Mississippi Embayment study area the empirical relationship of Kaka and Atkinson (2005) is used to predict peak ground motions for magnitudes below six and the relationship of Toro et. al., (1997) is used for earthquakes of magnitude six and larger. The relationship of Kaka and Atkinson (2005) will benefit from additional refinement to ensure that it is accurately portraying New Madrid Seismic Zone earthquakes. As they occur, ShakeMaps for events less than magnitude five should be compared to the Community Internet Intensity Maps to confirm the accuracy of the regression. For magnitudes larger than five a comparison with other large intra-cratonic earthquakes (e.g. Bhuj, India, earthquake, January 2001) may provide a clearer picture of ShakeMap. The relationship will need to be reassessed as new information is gathered and predictive models improve.

The instrumental intensity regression of Kaka and Atkinson (2005) is used as the default regression for the study area. The regression is significantly different than those developed for the Western United States and is presently the only available central and eastern United States regression. Atkinson (personal communication) plans to develop a relationship between peak ground velocity and MMI for the New Madrid region and work on the study will begin in the summer of 2005. A comparison of the two regressions will assist in determining where the higher than predicted Intensity levels are arising. If the two studies are similar then the attenuation relation should be examined.

The default ShakeMap amplification protocol of Borcherdt (1994) is transferable from the Western United States to the central and eastern United States and is adequate for the implementation of ShakeMap in the Mississippi Embayment. The benefits of Cramer’s (2004) protocols should be incorporated into the determination of ShakeMap’s amplification factors.

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. An update and expansion of the coverage area of the CUSEC Map is needed.

Finally, the density of stations needs to be improved. There are only 30 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 ShakeMaps depends on near-real-time data from a large number of on-scale, high quality seismographs.

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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
Comparison of soil types as described by Borcherdt (1994) and Bauer et. al, (2001)
(Bauer *et. al*, 2001).

Soil type	Generic Description found in Borcherdt (1994)	Avg. Shear Wave Velocity (feet/sec)	Central U.S. Deposits
A	Hard Rock	> 5,000	limestone, dolomite, & most unweathered sedimentary bedrock
B	Rock	2,500 – 5,000	some shales, weathered bedrock
C	Hard and/or stiff/very stiff soils; most gravels	1,200 – 2,500	some tills, gravels (cemented), most Tertiary/Cretaceous deposits which are sands, clays and gravels of the Mississippi Embayment
D	Sands, silts and/or stiff/very stiff clays, some gravels	600 - 1,200	tills, alluvium, lacustrine, loess, some sands, clays and gravels of the Mississippi Embayment
E_1	Small to moderate thickness (10 to 50 feet) soft to medium stiff clay, Plasticity Index > 20, water content > 40 percent	< 600	some lacustrine and loess deposits
E_2	Large thickness (50 to 120 feet) soft to medium stiff clay Plasticity Index > 20, water content > 40 percent	<600	
(F)	Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils.		Most alluvium deposits and sensitive materials that may fail in seismic induced landslides such as the Kope Formation near Cincinnati

Table 3
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
	0.4 - 2.0	3.3	3.0	2.6	2.3

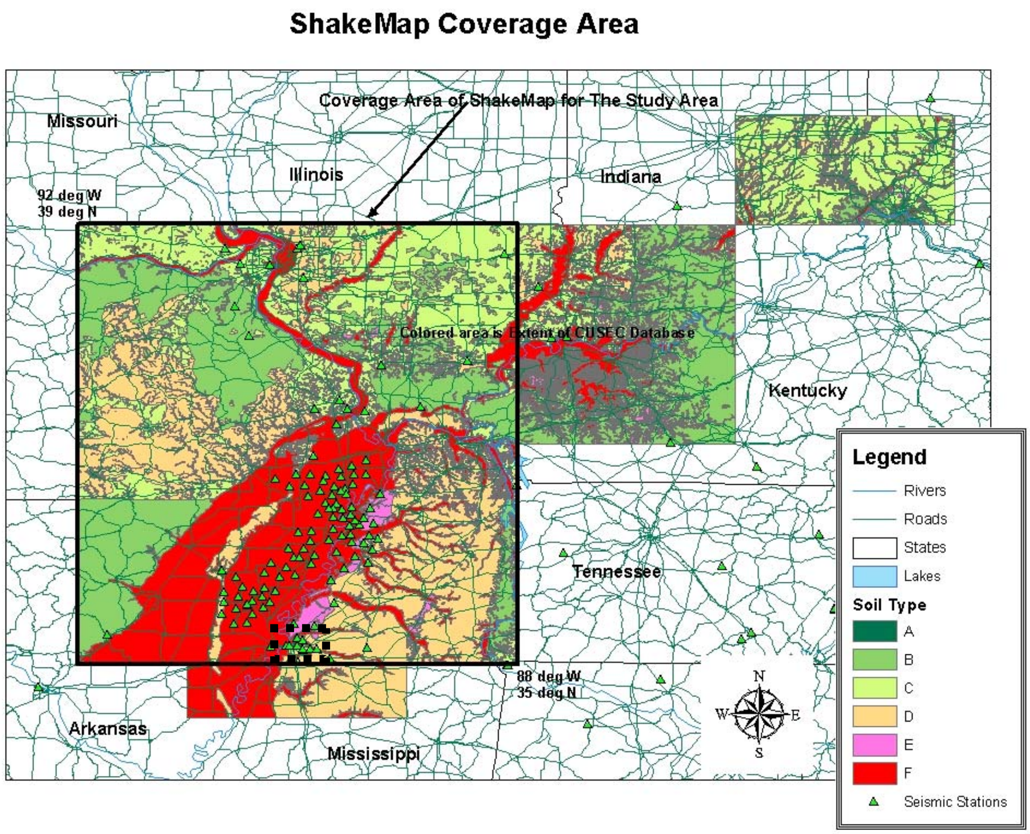


Fig. 1 Coverage area of ShakeMap for study area is in the rectangular box bounded by 92° West, 39° East, 88° West, 33° North. Colored area is the extent of the CUSEC database.

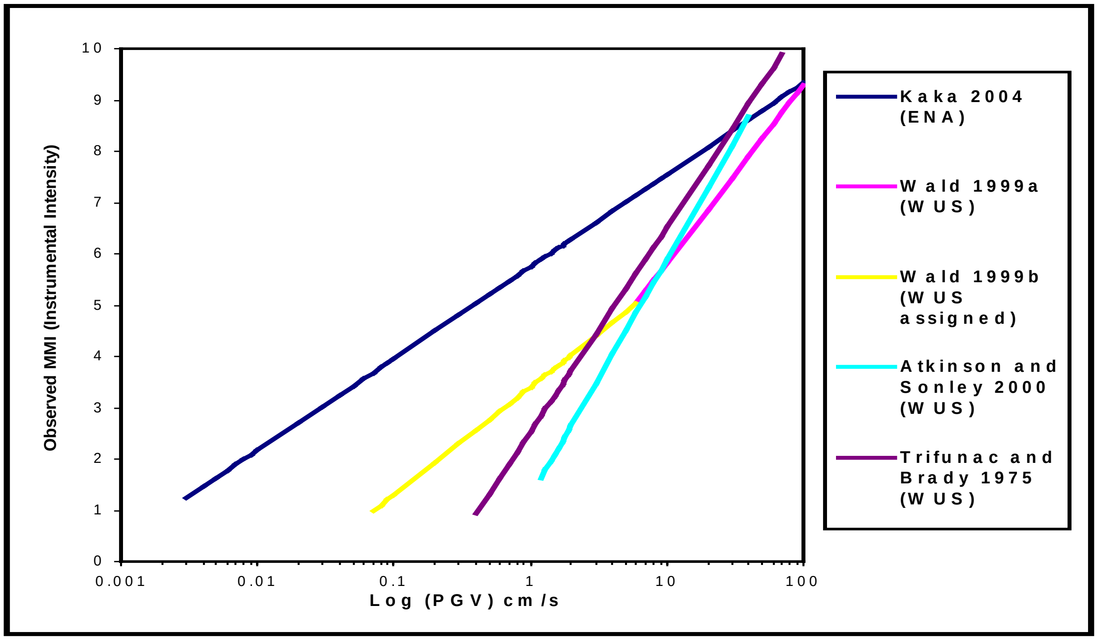


Fig. 2 MMI plotted against peak ground velocity for various Western United States and central and eastern United States regressions.

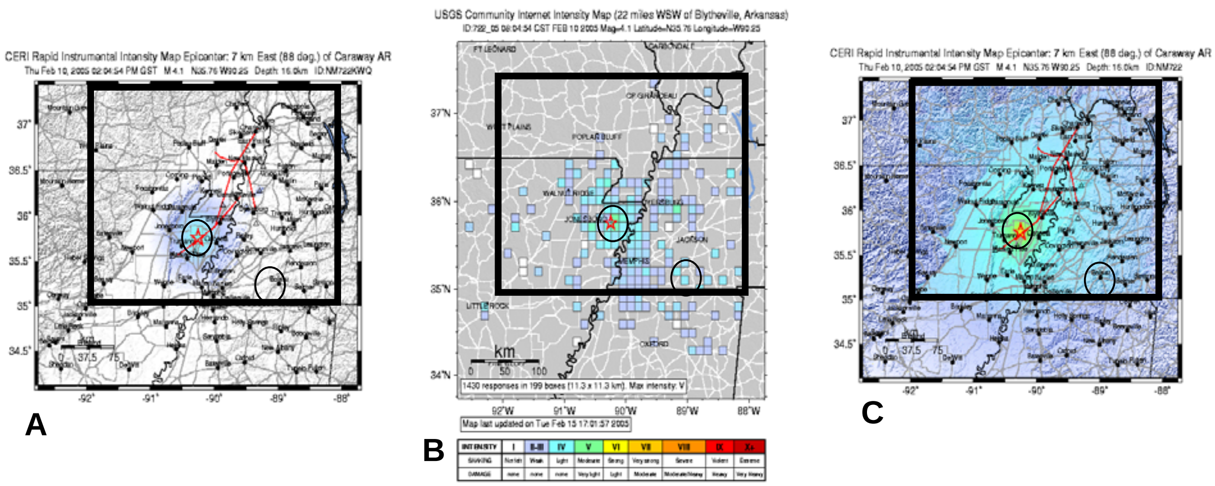
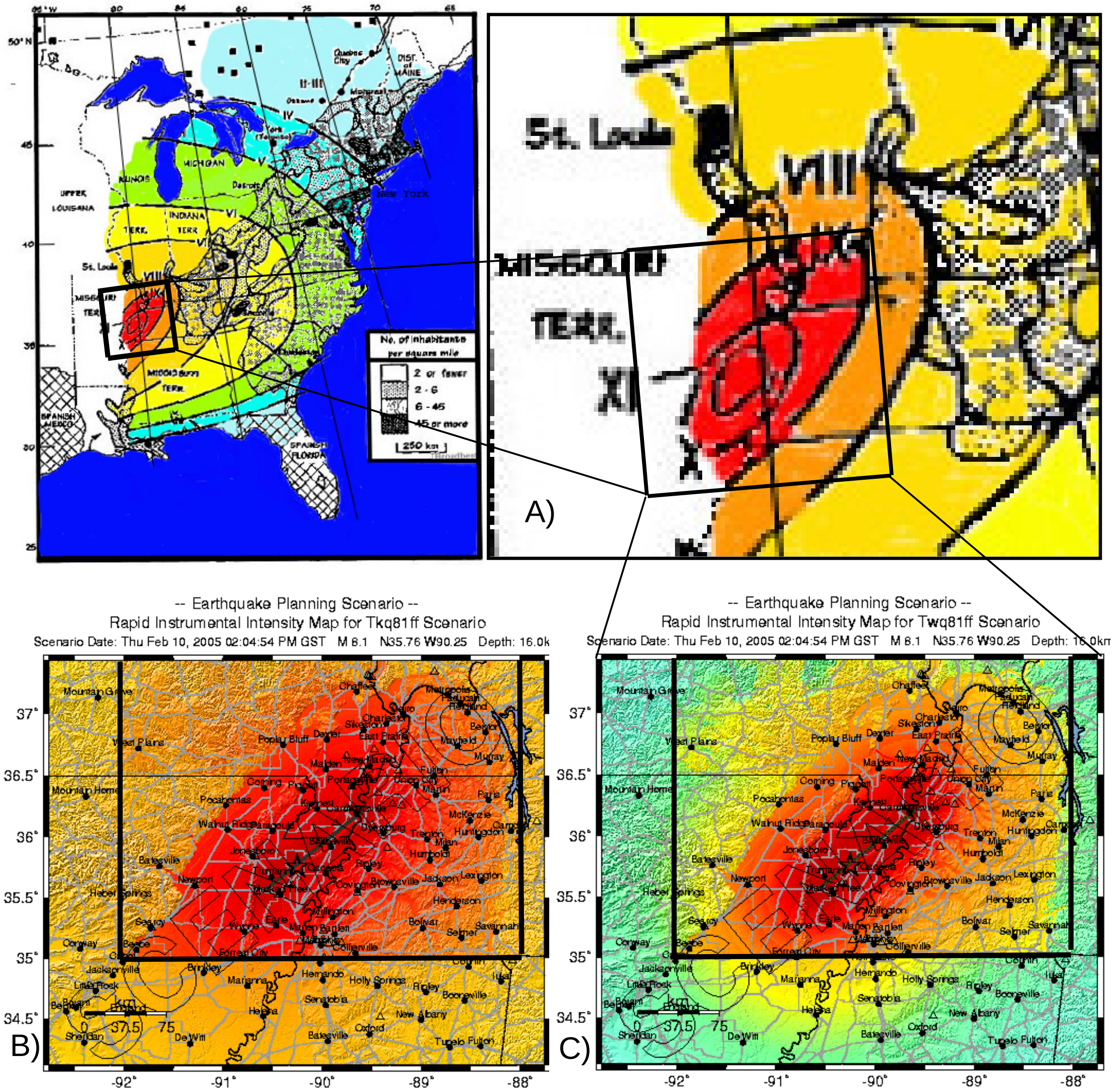


Fig. 3. ShakeMap intensities for the Feb. 10, 2005 Blytheville, Arkansas, M = 4.1 earthquake. Maps were created using attenuation relationship of Kaka and Atkinson (2005) and A) instrumental intensity regression developed by Wald *et al*., (1999a) B) is observed geocoded Intensities from Community Internet Intensity Maps (Wald *et al*., 1999b) and C) instrumental intensity regression developed by Kaka and Atkinson (2004). Insets are extent of applied amplification factors. Circles are for comparison of regressions.



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)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 4. Comparison of M = 8.1 Scenario to A) 1811-1812 New Madrid Sequence (After Johnston and Schweig, 1996), B) regression of Kaka and Atkinson (2004) and C) regression of Wald *et al.*, (1999a). The insets on the lower figures are the extent of amplification factors (see text for details). Inset on top figure is approximate area of the lower maps. Attenuation relationship of Toro *et. al.,* (1997) used for B and C.

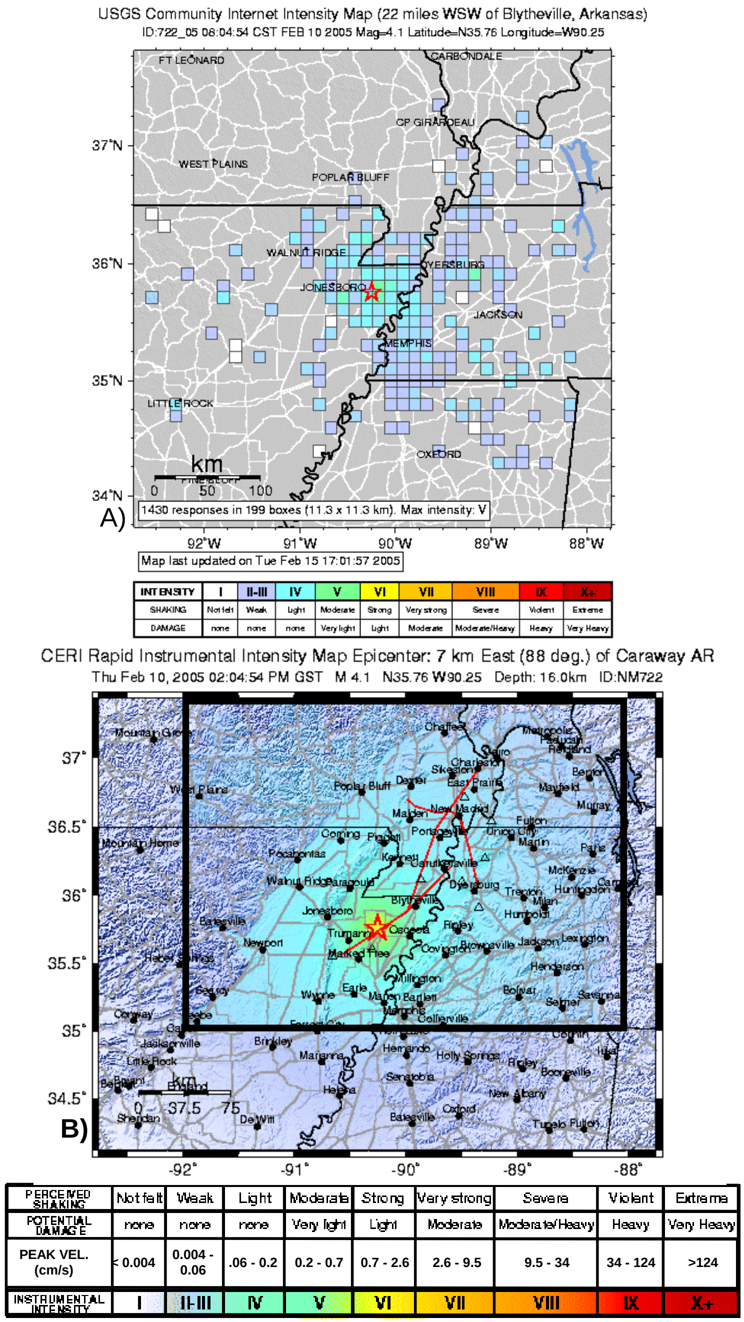
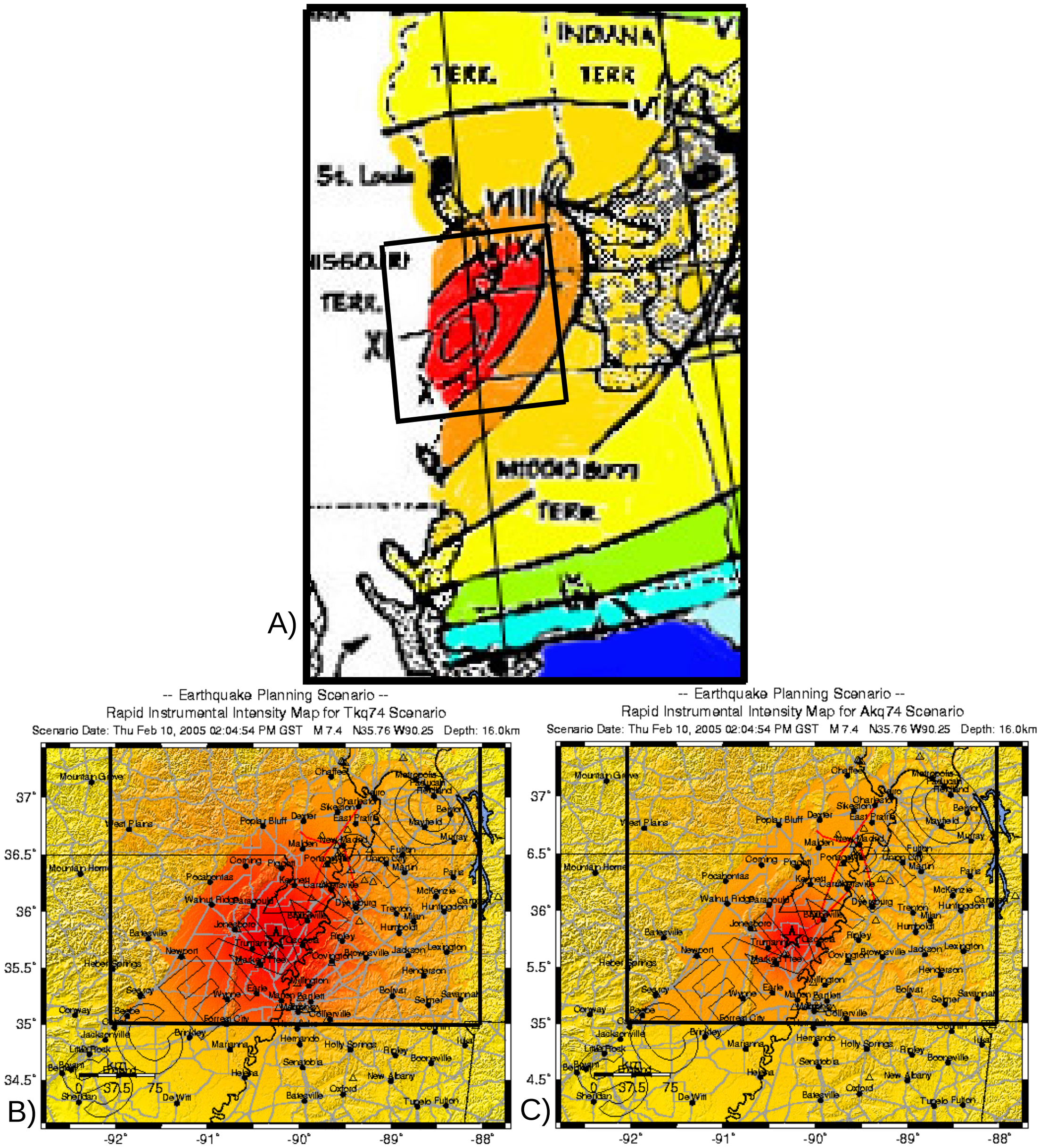


Fig. 5. A) Observed geocoded Intensities from Community Internet Intensity Map Wald *et al*., (1999b). B) ShakeMap intensity map for the Feb. 10, 2005 Blytheville, Arkansas, M = 4.1 earthquake. Map was created using attenuation relationship of Kaka and Atkinson (2005) and regression of Kaka and Atkinson (2004); Inset on lower panel is extent of applied amplification factors.



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 VEL. (cm/s)	< 0.004	0.004 - 0.06	.06 - 0.2	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+

Fig. 6. Comparison of M 7.4 Scenario to A) 1811-1812 New Madrid Sequence (After Johnston and Schweig, 1996), B) Attenuation relationship of Toro (1997) and C) Attenuation relationship of Atkinson and Boore (1995). Regression of Kaka and Atkinson (2004) used for both scenarios. The insets on the lower figures are the extent of amplification factors.