Bulletin of the Seismological Society of America, Vol. 93, No. 4, pp. 1841–1846, August 2003

Site-Specific Seismic-Hazard Analysis that is Completely Probabilistic

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Abstract When a site-specific probabilistic ground-motion estimate is required, the full site-amplification distribution should be used instead of a single deterministic median value. A probabilistic methodology using site-amplification distributions to modify rock ground-motion attenuation relations into site-specific relations prior to calculating seismic hazard has been developed and applied at two selected sites in the central United States: Memphis, Tennessee, and Paducah, Kentucky. The use of a completely probabilistic approach can make about a 10% difference in ground-motion estimates over simply multiplying a bedrock probabilistic ground motion by a median site-amplification factor at a 1 in 2475 annual probability of exceedance and even larger differences at smaller probabilites of exceedance. The value of this approach is that a probabilistic answer incorporating the uncertainty in our knowledge of site amplification of ground motions can be calculated.

Introduction

For the last two decades, the state of practice in calculating a site-specific ground motion has been to calculate probabilistic bedrock ground motion and then multiply it by a deterministic site-amplification factor. If site amplification were truly single valued, then this would imply that there is no uncertainty in its calculation, and the resulting site-specific ground motion would still be a probabilistic result. However, there is uncertainty in estimating site amplification, but the state of practice is to use the median site-amplification factor. Thus, the resulting ground motion is a hybrid answer that is no longer truly probabilistic.

To overcome this problem one must calculate the effects of uncertainty on the estimate of a site-amplification factor and use the resulting site-amplification distribution in a probabilistic methodology. Where a truly probabilistic site-specific ground motion is desired, this would be a state-of-the-art approach to estimate the answer. McGuire *et al.* (2001) and A. Frankel (personal comm., 2001) have suggested that site-amplification distributions be used to modify bedrock ground-motion attenuation relations into site-specific relations prior to the calculation of seismic hazard. Lee (2000) developed a methodology to calculate bedrock probabilistic ground motions and site amplifications separately and then probabilistically combine the results. Silva (in Bechtel Jacobs, 2002) has implemented another approach by constructing a site-specific ground-motion attenuation relation for each period of interest using a source-path-site random vibration theory (RVT) model that includes site amplification and its variability.

This short note focuses on an implementation of the McGuire *et al.* and Frankel approach of modifying bedrock ground-motion attenuation relations prior to making hazard calculations. Examples for the central United States are provided to illustrate the results of this approach.

Methodology

In general, a ground-motion attenuation relation predicts ground motion as a function of earthquake magnitude and distance from the source. For a given magnitude and distance, there is a distribution of possible ground motions representing the observed random variability in earthquake ground motions about a central value. These ground-motion probability distributions are used in probabilistic seismic-hazard analyses to estimate the probability of exceeding a given level of ground motion (Cornell, 1968; Reiter, 1990).

For a given site, the probability, P, of exceeding a specific ground motion (Reiter, 1990, equation 10.2) is

$$P(A > A_0) = \Sigma_I \alpha_I \int_{\mathrm{M}} \int_{\mathrm{R}} f_I(M)\, f_I(R)\, P(A > A_0 \mid M,R)\, dR\, dM, \tag{1}$$

where A is a ground-motion parameter (i.e., peak ground acceleration [PGA] or spectral acceleration [Sa]), A_0 is the ground-motion level to be exceeded, α_{I} is the annual rate of occurrence of the ith source, M is magnitude, R is distance, $f_I(M)$ is the probability density distribution of earthquake magnitude of the ith source, and $f_I(R)$ is the probability density distribution of distance from the ith source. In equation (1), the two integrals are over M and R, and the summation is over all the sources in the model. The vertical line means "given the following value(s)" (M and R in this case), and hence $P(A > A_0 \mid M,R)$ is the probability of exceeding ground motion A_0 given an earthquake of magnitude M at distance R. This ground-motion probability distribution comes from a ground-motion attenuation relation, such as Toro et al. (1997), and is assumed (Reiter, 1990) to be lognormal with a median value and a logarithmic standard deviation.

In eastern North America (ENA) the ground-motion attenuation relations are usually for a site on bedrock. Hence in equation (1)

$$P(A > A_0 \mid M,R) = P(A_r > A_0 \mid M,R), \quad (2)$$

where A_r is the ground motion on bedrock. Usually in a site-specific analysis, A_r is assumed to be for a hard-rock site condition National Earthquake Hazards Reduction Program ([NEHRP], soil class A). ENA ground-motion attenuation relations can correspond to differing site conditions ranging from NEHRP soil class A to B/C boundary, and when used in combination are adjusted to a common site condition (see Frankel *et al.*, 1996, 2002).

For a site-specific analysis on soil, a site-specific attenuation relation $P(A_s > A_0 \mid M,R)$ must be determined for use in equation (1), where A_s is the ground motion for the soil site condition. In the ENA, where empirical ground-motion attenuation relations do not exist, site amplification is estimated from a soil profile (shear-wave velocity V_s, shear-wave attenuation Q_s, and soil density as a function of depth) and dynamic soil properties (modulus and damping) for high strains. To incorporate uncertainty, the soil profile and dynamic soil properties are randomized to develop a site-amplification distribution P(sa). For this article P(sa) is the probability of A_s given an input of A_r to the base of the soil column and is represented by

$$P(\mathrm{sa}) = P(A_s \mid A_r). \quad (3)$$

This site-amplification probability distribution could have any shape (equally likely, Gaussian, lognormal, etc.), but in this article it will be assumed that it is a lognormal distribution with a median value and a logarithmic standard deviation.

Implicit in equation (3) is the assumption that the site-amplification distribution is only dependent on the input ground motion at the base of the soil column. This assumption is also implicit in the methodology used to estimate the site-amplification distributions described earlier. Lee (2000) and Silva (Bechtel Jacobs, 2002) allowed for an additional magnitude dependence in their site-amplification distributions. This is because they both assumed that the site-amplification distribution is determined by using Silva's RVT approach incorporating source and path modeling as well as the site model previously described. The approach proposed in this article uses the site-amplification distribution to modify existing ground-motion attenuation relations, which already incorporate the source and path modeling. For this latter case, equation (3) is sufficient, although a more complex site-only model could be developed in a manner similar to that described subsequently.

Given $P(A_s \mid A_r)$ for a soil site and $P(A_r > A_0 \mid M,R)$ from a bedrock attenuation relation,

$$P(A_s = A_0 \mid M,R) = \int_{Ar} P(A_s \mid A_r) \; P(A_0 = A_r \mid M,R)\, dA_r, \quad (4)$$

where

$$P(A_0 = A_r \mid M,R) = d[1 - P(A_0 > A_r \mid M,R)]/dA_0. \quad (5)$$

By definition, equation (5) determines the probability of A_0 equaling A_r given M and R from the derivative of the compliment of the probability of A_0 exceeding A_r given M and R. And equation (4) determines the probability of A_s equaling A_0 given M and R by integrating the product of the probability of A_s given A_r times the probability of A_0 equaling A_r given M and R over all A_r (i.e, summing the combinations of input-bedrock ground motion and site-amplification probabilities that give $A_s = A_0$).

From equation (4) one can easily determine $P(A_s > A_0 \mid M,R)$:

$$P(A_s > A_0 \mid M,R) = 1 - \int_{A_s:-\infty\to A_0} \int_{Ar} P(A_s \mid A_r) \; P(A_0 = A_r \mid M,R)\, dA_r\, dA_s. \quad (6)$$

Note that the integral involving A_s is from minus infinity to A_0. Equation (6) integrates all the probabilities for $A_s \le A_0$ and takes its compliment to obtain the soil–site ground-motion attenuation relation to use in equation (1).

J. Marrone (personal comm., 2002; Bechtel Jacobs, 2002) suggested an improvement by moving the integration involving A_s inside the integration involving A_r in equation (6). By definition

$$P(A_s \le A_0 \mid A_r) = \int_{A_s:-\infty\to A_0} P(A_s \mid A_r)\, dA_s. \quad (7)$$

So equation (6) becomes

$$P(A_s > A_0 \mid M,R) = 1 - \int_{A_r} P(A_s \le A_0 \mid A_r) \; P(A_0 = A_r \mid M,R)\, dA_r. \quad (8)$$

Equation (7) is the cumulative probability density distribution of A_s given A_r. The advantage of using a cumulative probability density distribution is that it is easier and more accurate to calculate at a given ground-motion value than to discretize the probability density distribution of equation (3) for use in equation (6). This is demonstrated in the next section.

Numerical Implementation

Prior to their use in computer codes, a spreadsheet was used to check on the limitations of implementing equations (6) and (8). After selection of the numerical approach to implement, the computer codes used by the U.S. Geological Survey's (USGS's) national seismic-hazard mapping project were then modified and checked using the spreadsheet results. Validating comparisons of the approach of this article with that of Lee (2000) and Silva are summarized from Bechtel Jacobs (2002).

Table 1 shows the results of the spreadsheet check. The top line of Table 1 is the acceleration-bin central values used in the spreadsheet calculations. The values of A_r in this example are those used by the national seismic-hazard mapping project. The ground-motion values shown in Table 1 increase by a factor of 1.4 between bin values. As a test of the accuracy of the ground-motion estimates obtained using this factor of 1.4 between A_r values, the factor was reduced to 1.2. The resulting ground-motion estimates at 2%-in-50-year probability of exceedance were only different by less than 5%, generally much less, over the entire central and eastern United States (2,442,036 sites). Thus, the factor of 1.4 between A_r values is sufficient for reliable seismic-hazard estimates at soil sites using the methodology of this article.

The second line of Table 1 shows the values of $P(A = A_r)$ for each A_r bin, where bin boundaries are the geometric mean of the central A_r values below and above the boundary. (Because the ground-motion attenuation relations are lognormal distributions, it is more appropriate to use the geometric mean instead of the arithmetic mean of the central A_r values. In practice, the difference in the final ground motion determined for these two choices [geometric versus arithmetic] is less than 1%.) For the first A_r bin ($0.005g$), the lower boundary is minus infinity and, for the last A_r bin ($2.15g$), the upper boundary is plus infinity. J. Marrone (in Bechtel Jacobs, 2002) chose to truncate these limits at minus and plus 3σ and renormalize. This does not affect the final ground-motion estimate because of the very small probabilities in these tails (below -3σ and above 3σ) and thus is a matter of personal choice. $P(A = A_r)$ sums to one as it should. As indicated at the top of Table 1, $P(A = A_r)$ is for an M,R pair that gives a hard-rock median ground motion of $0.85g$ and has a ln σ (natural logarithmic standard deviation) of 0.75.

The first and last $P(A = A_r)$ values (for $A_r = 0.005g$ and $2.15g$) contain probabilities for the tails of the $P(A = A_r)$ Gaussian distribution, as shown in Table 1. Normally, one would expect small probability values (<0.1) in the first and last $P(A = A_r)$ bins. This is assumed to be true, but in this example, if the hard-rock A_r is very small ($<0.01g$) or very large ($>1.5g$), the first or last bin will have a larger than expected probability instead of the assumed very small probability. For very small median A_r, the ground motions are small and remain so after the adjustment for site amplification. However, for very large median ground motions, this could be a potential problem. The impact of this potential inaccuracy can be reduced by the capping of large ground motions, as done in the computer codes of Frankel *et al.* (1996, 2002). It can also be reduced by extending hard-rock ground-motion bins to larger values.

The third and fourth lines of Table 1 indicate the site-amplification distribution used as part of this example (a synthesized example for illustrative purposes only). The third line shows the rock ground-motion–dependent median amplification, and the fourth line shows its standard deviation (σ) in natural logarithms (base e) that are used to represent the site amplification. Lines 3 and 4 represent the entire soil site-amplification response at the site, which is assumed to be dependent only on the input rock ground motion, as discussed earlier. Although this example uses a constant logarithmic σ, typically it is not a constant but increases with increasing rock ground motion from about 0.25 to about 0.35. While the ground-motion bin width of 1.4 used in Table 1 is comparable to the site-amplification σ, it is sufficient for reliable seismic-hazard estimates ($<5\%$ different from estimates obtained using a ground-motion bin width of 1.2). A smaller ground-motion bin width can be used if desired, although the resulting site-specific ground-motion estimates seem not be very sensitive to the bin width used.

Line 5 of Table 1 shows the resulting $P(A > A_s)$ from using equation (8). Equation (6) can also be used to obtain $P(A > A_s)$, but care must be taken or values different than shown in line 5 of Table 1 can be incorrectly obtained. In equation (6) the probability density distribution $P(A_s \mid A_r)$ must be calculated instead of the cumulative probability density distribution $P(A_s \le A_0 \mid A_r)$. If discrete bins for A_s are centered on the same bin centers as A_r in line 1 of Table 1, then when the probability density distribution $\int_{A_r} P(A_s \mid A_r)\, P(A_0 = A_r \mid M,R)\, dA_r$ is cumulated over A_s to obtain $P(A_s > A_0)$, these values end up really being for the lower bin boundaries of A_s, which are greater than those of line 5 of Table 1. As pointed out by J. Marrone (personal comm., 2002), the best and simplest way to avoid this problem is to use equation (8), although the careful selection of A_s bin boundaries to correspond to the values listed in line 1 of Table 1 also can avoid this problem.

Figure 1 shows the transformation in a PGA hazard curve from exceeding A_r to exceeding A_s as shown in Table 1. As expected, at small ground motions ($<0.3g$) the site-specific probabilities of exceedance of A_s are larger than that for A_r, and vice versa for larger ground motion ($>0.3g$).

For verification, Bechtel Jacobs (2002) presented a comparison of results using the methodology of this article and those of Lee (2000) and Silva (table 8-1). As a reminder, this article modifies the rock ground-motion attenuation relation with the site-amplification distribution prior to the probabilistic seismic-hazard calculation, Lee (2000) combined the site-amplification distribution with the rock probabilistic seismic-hazard curve (after its calculation), and Silva generated a site-specific ground-motion amplification relation prior to calculating seismic hazard from a source–path–site RTV model that includes the uncertainty in site amplification. The Bechtel Jacobs comparison is for the same site-amplification distribution, although different from the Risk Engineering (1999) distribution used in this article and the hard-rock ground-motion model. The comparison is

Table 1
Results from the Spreadsheet Check of the Numerical Implementation for a Median Rock Ground Motion of $0.85g$ with a $\ln \sigma$ of 0.75

Bin A_r, A_s (g):	0.005	0.007	0.0098	0.0137	0.0192	0.0269	0.0376	0.0527	0.0738	0.103	0.145	0.203	0.284	0.397	0.556	0.778	1.09	1.52	2.13
$P(A = A_r)$	2E-11	3E-10	4.7E-9	5.9E-8	6.2E-7	5.2E-6	3.6E-5	0.0002	0.0009	0.0036	0.0115	0.0294	0.0617	0.1066	0.1514	0.1763	0.1675	0.1315	0.1591
Site amplification distribution																			
Median	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.989	1.902	1.783	1.555	1.294	1.130	0.9054	0.7424	0.6107	0.55	0.55	0.55
$\ln \sigma$	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Results for $P(A > A_s)$																			
from equation (8)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.9997	0.9976	0.9833	0.9127	0.7183	0.4587	0.2629	0.1191	0.0266	0.0017

for a 1 in 2475 annual probability of exceedance. The values for PGA are $0.47g$, $0.48g$, and $0.52g$ for the approaches of this article, Lee, and Silva, respectively. Values for 0.1-sec spectral acceleration (Sa) are $0.89g$, $0.90g$, and $0.96g$; and for 1.0-sec Sa, they are $1.07g$, $1.07g$, and $1.21g$. Clearly the method used in this article and the method used by Lee (2002) agree very well in their results (a difference of $0.01g$ or less). The estimates using Silva's method are a little larger, which is expected because his overall uncertainty is a little larger using his one-step approach than the two-step approaches of Lee and this article. But the differences are only 5%–15%.

Results

Equation (8) has been used to implement this methodology in the same computer codes used to calculate seismic hazard in the central and eastern United States by the USGS national seismic-hazard mapping project (the website for the *unmodified* codes is http://geohazards.cr.usgs.gov/eq/html/hazsoft.html). (Please note that the USGS national seismic-hazard maps are only generated for uniform site conditions and are not site specific. The modified codes used for this article are not official codes of the national seismic-hazard mapping project.) This implementation expects the site-amplification distribution at each A_r to be represented by a lognormal probability density distribution with a median value and a natural logarithmic standard deviation. If desired, other site-amplification distributions can be implemented by the methodology of this article.

Figure 2 shows a comparison of site-specific mean hazard curves using the completely probabilistic and hybrid (median site amplification times probabilistic hard-rock ground motion) approaches plus the hard-rock hazard curve on which they are based. The site (37.1° N, 88.8° W) is near Paducah, Kentucky, and uses the PGA site-amplification distribution for Paducah developed by W. Silva (Risk Engineering, 1999). The seismic-hazard model is that of Frankel *et al.* (2002), and the calculations have been done using the hard-rock ground-motion relations of Toro *et al.* (1997), Frankel *et al.* (1996, corrected to hard rock using a factor of $1/1.52 = 0.658$), Atkinson and Boore (1995), Somerville *et al.* (2001), and Campbell (2003) weighted 1/4, 1/4, 1/4, 1/8, and 1/8 (weighting of August 2002 as documented at http://geohazards.cr.usgs.gov/eq/html/ceus2002aug.html).

In Figure 2, the ground motions predicted by the completely probabilistic approach are generally higher than that predicted by the hybrid approach, particularly at large PGA ($>0.5g$). At small PGA ($<0.5g$) the differences are much less than $0.1g$ and the completely probabilistic values can be less than the values of the hybrid approach. By understanding which part of the ground-motion distribution contributes most to the probabilistic hazard calculation (lower tail, near median, or upper tail), the good agreement of the hybrid method results at small ground motions but poor agreement at higher ground motions can be understood. This is accomplished by seismic-hazard deaggregation (see

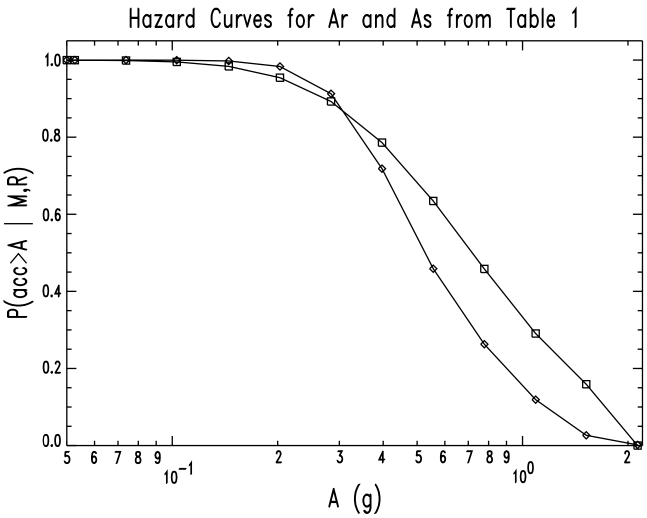

Figure 1. Comparison of hard-rock PGA (A_r) and soil PGA (A_s) probability of exceedance (hazard) curves from Table 1 for a specific magnitude (*M*) and distance (*R*). Squares, hard-rock A_r; diamonds, soil A_s.

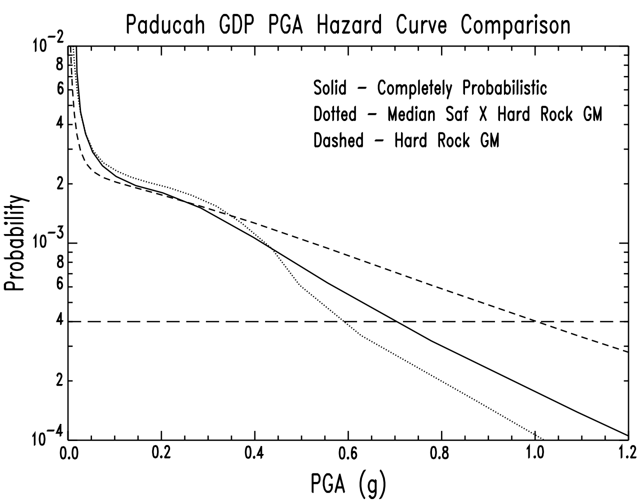

Figure 2. Comparison of Paducah, Kentucky, mean hazard curves for the completely probabilistic and hybrid methods and for hard rock. See text for seismic-hazard model details. GDP, gaseous diffusion plant; PGA, peak ground acceleration; Saf, site amplification factor; GM, ground motion.

Harmsen *et al.*, 1999). In general, deaggregation results indicate that at small PGA the contribution predominately comes from below or near the median PGA of the hazard curve. Thus using the median site-amplification times this near median hard-rock ground motion gives similar results to those of the completely probabilistic method. However, at larger ground motions, deaggregation indicates the contribution is mainly from the upper tail of the ground-motion probability density distribution. Thus the completely probabilistic method gives ground-motion estimates that are above those from the hybrid method.

Table 2 gives some example hazard calculations for different site conditions at Paducah, Kentucky (37.1° N, 88.8° W) and Memphis, Tennessee (35.2° N, 90.0 °W). The ground-motion estimates shown are for the 1 in 2475 annual probability of exceedance PGA and 1-sec Sa. The calculations for Memphis use Toro and Silva's (2001) site-amplification distributions for Quaternary (lowland floodplain sediments) and Tertiary (upland sediments) average *S*-velocity profiles for the Mississippi embayment. Table 2 gives hard-rock, hybrid methodology, and completely probabilistic methodology estimates of ground motions.

From the hybrid and completely probabilistic estimates in Table 2, we see that, at Memphis, the differences for PGA and 1-sec Sa are all very small ($<0.05g$). But at Paducah, the differences are larger ($>0.1g$). And they are more of an engineering concern ($>0.5g$). At both sites, PGA values are expected to be reduced from the hard-rock estimates due to nonlinear soil behavior. But at 1-sec Sa, soil-layer resonances amplify ground motions above the hard-rock site conditions. At Paducah, the soil thickness is about 100 m, while at Memphis, it can exceed 1 km, both of which give rise to long-period amplification. Paducah has a fundamental site resonance near 1 sec, and Memphis has a fundamental site resonance at 4–5 sec (Bodin and Horton, 1999).

The results for Paducah, Kentucky, in Table 2 are higher than those of Bechtel Jacobs (2002). Table 8-1 of the Bechtel Jacobs report indicates a site-specific PGA of about $0.5g$ and a 1.0-sec Sa of about $1.1g$. There are several reasons for these differences. First, Bechtel Jacobs (2002) used a revised site-amplification distribution that has a little more ground-motion deampification than the one by Risk Engineering (1999) used in this article. Second, based on more recent paleoseismic and 1811–1812 intensity studies (Tuttle *et al.*, 2002; Hough *et al.*, 2002), the Frankel *et al.* (2002) update of the national seismic-hazard model used in this article shortens the mean recurrence interval and decreases the average magnitude of the New Madrid characteristic earthquake (500 years and *M* 7.7) over the Frankel *et al.* (1996) (1000 years and *M* 8.0) and Risk Engineering (1999) (850

Table 2
Site-specific ground motion hazard (*g*) for 1 in 2475 annual probability of exceedance (2% exceedance in 50 years)

	Hard Rock	Hybrid	Completely Probabilistic
PGA			
Memphis, TN			
Lowlands (Q)	0.56	0.29	0.27
Uplands (T)	0.56	0.34	0.30
Paducah, KY	1.00	0.59	0.70
1.0-sec Sa			
Memphis, TN			
Lowlands (Q)	0.29	0.80	0.78
Uplands (T)	0.29	0.66	0.65
Paducah, KY	0.52	1.06	1.21

Based on the Frankel *et al.* (2002) national seismic hazard model and Silva's site-amplification distributions (Risk Engineering, 1999; Toro and Silva, 2001). Q, Quaternary sediments; T, Tertiary sediments; PGA, peak ground acceleration; Sa, spectral acceleration.

years and M 8.0) models. Close in to the New Madrid seismic zone, the shortened mean recurrence interval dominates more than the decreased mean characteristic magnitude, which leads to some increase in seismic hazard. Lastly, the Frankel *et al.* (2002) update uses five ground-motion attenuation relations with a higher combined median than the Risk Engineering (1999) model's median corresponding to the Toro *et al.* (1997) relationship, particularly for PGA. This also increases seismic hazard some. Thus the Bechtel Jacob (2002) results represent an estimate to the low side of seismic-hazard estimates at Paducah, Kentucky, and the results of this article are more in line with current scientific understanding of New Madrid earthquake recurrence, characteristic magnitude, and ground-motion attenuation.

Summary

When a site-specific probabilistic ground-motion estimate is required, the full site-amplification distribution should be used instead of simply a deterministic median value, particularly at larger ground motions ($>0.5g$). At some sites, such as Paducah, Kentucky, the use of a completely probabilistic approach can make a $0.1g$ or greater difference over a hybrid approach using probabilistic hard-rock ground motions multiplied by a deterministic median site amplification. At other sites, such as Memphis, Tennessee, the difference is less. The larger probabilistic ground-motion estimates at higher ground motions ($>0.5g$) over the hybrid approach are due to the predominant contribution from upper-tail ground-motion probabilities of exceedance in the probabilistic calculations as revealed by seismic-hazard deaggregation. The value of the completely probabilistic approach is that a true probabilistic estimate can be calculated that incorporates the uncertainty in our knowledge of site amplification of ground motions.

Using the site-amplification distributions of Risk Engineering (1999) and Toro and Silva (2001), the completely probabilistic PGA and 1.0-sec Sa are $0.7g$ and $1.2g$ at Paducah, Kentucky. At Memphis, Tennessee, the probabilistic PGA and 1-sec Sa are about $0.3g$ and $0.6g$–$0.8g$, respectively. The PGA results show deamplification due to nonlinear soil response, while the 1.0-sec Sa results are amplified by soil thickness resonances.

Acknowledgments

The author wishes to thank Chuck Mueller, Mark Petersen, and Steve Harmsen for insightful and helpful reviews of the manuscript. Their suggestions and comments are greatly appreciated and greatly improved the manuscript.

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Manuscript received 8 October 2002.