13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2834

POST-EARTHQUAKE ESTIMATION OF SITE-SPECIFIC STRONG GROUND MOTION

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SUMMARY

In the days, months, and sometimes years following a significant earthquake, there is often a need for an estimate of the strong ground motion that is likely to have occurred at a given site. A common example of the use of these estimates is for assessing damage that may not be readily observed by site inspection or that may have been partially or completely repaired during the period between the earthquake and the present time. When the site is located at or very close to a free field ground motion recording station, the problem is easily solved, as the ground motion at the site can be assumed to be that of the recording station. However, when the site is located relatively far from the a ground motion recording station (e.g., greater than 1 km), or when there are two or more recording stations that are located in the vicinity of the site, the problem is not so easily solved. Additional complications are introduced when the site conditions at the site and the recording station(s) are different, and when the ground motion propagation path is not the same between the seismic source and the site and between the seismic source and the recording station(s). This paper presents a method for the post-earthquake estimation of site-specific strong ground motion. Also included is a method for quantifying the level of confidence associated with the ground motion estimate. An illustrative example is included.

INTRODUCTION

Following a significant earthquake, an engineering evaluation of damage to a structure requires an accurate estimation of the shaking at the building site. Estimation of ground shaking throughout a region is typically based on three primary approaches: (1) spatial interpolation of recorded ground motion; (2) attenuation of motion from the seismic source as a function of magnitude, distance, and soil conditions based on models developed from the recorded ground motion and/or from recorded ground motion in several previous events; or (3) theoretical simulation of motion based on a seismological model of the seismic source, path to the site including soil conditions and topographical features, and event parameters such as directivity of rupture. There is usually overlap among the approaches, e.g., interpolation schemes often incorporate empirical attenuation or theoretical ground motion models, attenuation models often

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follow functional forms suggested by theoretical models, and theoretical models are often fit to empirical data [1].

An example of the estimation of the regional distribution of strong ground motion using the combination of recorded data and empirical attenuation models is the ShakeMap [2] shown in Figure 1. ShakeMaps are generated automatically following earthquake events, using spatial interpolation of data from recording stations. For areas where recording station density is low, attenuation models are used to create virtual stations for use in the spatial interpolation scheme.

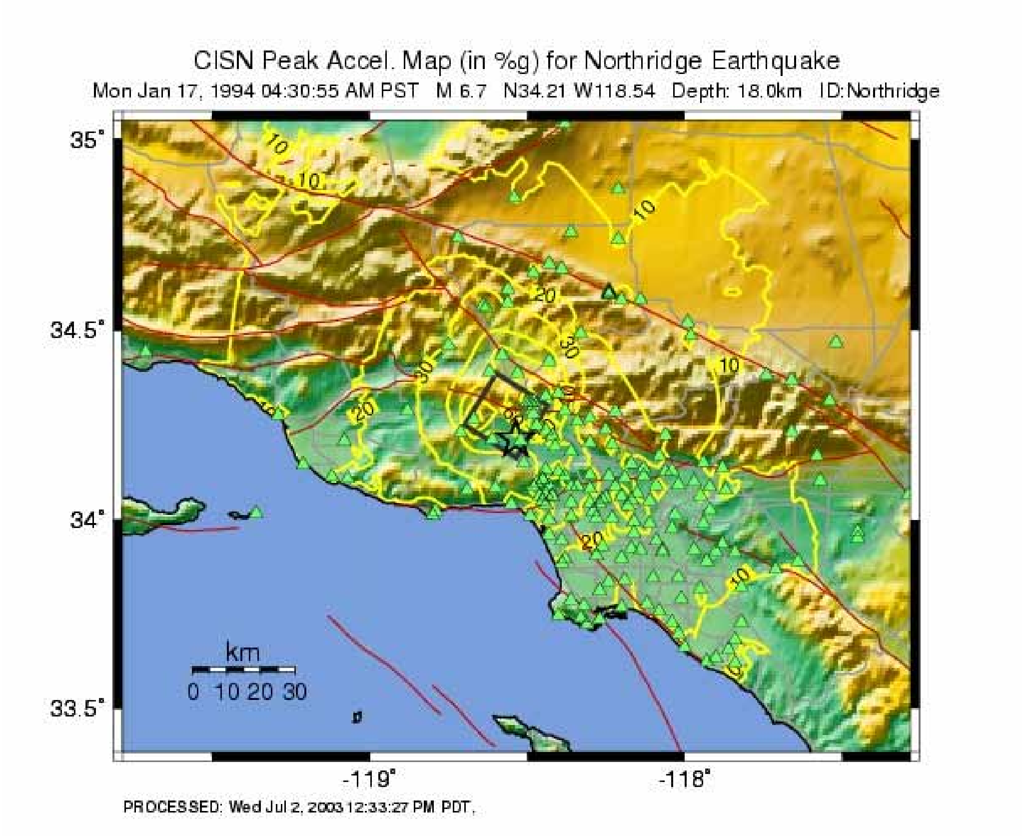

Figure 1 **ShakeMap showing contours of peak ground acceleration from the 1994 M 6.7 Northridge earthquake [2].**

A second example of the estimation of the regional distribution of strong ground motion are the method developed by Thrainsson et al. [3]. The method uses the combination of recorded data and theoretical simulation models to interpolate ground motion at points between ground motion recording stations. The theoretical simulation in the frequency domain is based on the propagation of Fourier amplitude and phase angle from the seismic source and from the locations of recorded motion. The authors also use the method to interpolate time histories at locations between recording stations.

A last example of the estimation of the regional distribution of strong ground motion is the contour maps of ground motion from the 1994 Northridge earthquake developed by Somerville et al. for the SAC Steel Frame project [4]. This method uses empirical attenuation relationships as the base estimate for all points in a grid used to map the contours. The grid values are then modified based on the data recorded at nearby strong motion stations to account for amplitude and duration effects of rupture directivity. Figure 2 shows one of the contour maps provided in [4].

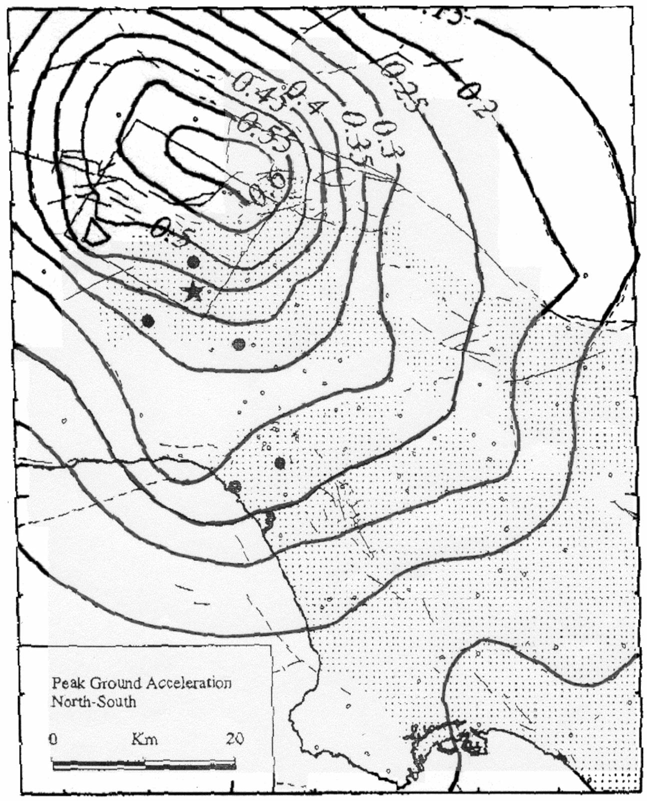

Figure 2 Contour map of peak ground acceleration in the north-south direction from the 1994 M 6.7 Northridge earthquake [4].

The method presented in this paper for the post-event estimation of site-specific strong ground motion relies on an interpolation of the data recorded at nearby strong motion stations, where the interpolation is based on a weighted average. Only free field stations (housed in instrument structures or small buildings) that are located on the same soil conditions as the site are included in the average. The weights are determined as a function of the inverse distance between the stations and the site and a subjective measure of the quality of the recording station data, i.e., how well the data represent the true free field ground motion in the vicinity. An empirical attenuation relationship is used to adjust the weighted average to account for the distances between the site and the epicenter and between the recording stations used in the average and the epicenter.

This method has been used over the past three years for more than 50 forensic evaluation cases of earthquake damage from the M 6.7 1994 Northridge earthquake. The site-specific ground motion estimates (in the form of horizontal and vertical acceleration response spectra) are used in structural analyses to simulate the performance of the buildings. Given the long time period between the earthquake and the forensic evaluation, it is difficult to determine from field investigation alone how the structure performed during the earthquake. In many cases repairs have been made or the presence or absence of damage has been obscured by remodeling of the structure. Structural analyses using reliable estimates of ground shaking at the site are critical for a complete and accurate forensic evaluation.

In recent forensic evaluations of earthquake damage, the question of confidence in the final assessment has been raised, i.e., the authors have been asked how confident they are in their final determination of the cause and extent of observed and/or simulated damage. There are several sources of uncertainty in the forensic evaluation process for which probabilistic analyses can be done to help quantify confidence. In this paper, the issue of confidence is limited to one step in the process – the estimation of the site-specific ground motion estimate. A method is proposed for quantifying the level of confidence in the site-specific ground motion estimate by comparing it to a probability distribution developed from available empirical attenuation relationships that are consistent with the faulting mechanism and site conditions.

The remainder of this paper describes the steps in the method for estimating site-specific strong ground motion in the form of horizontal and vertical acceleration response spectra and the procedure for providing a corresponding level of confidence in the estimate. An example follows to illustrate the estimation method and confidence quantification procedure.

ESTIMATION OF SITE-SPECIFIC STRONG GROUND MOTION

The method for estimating site-specific strong ground motion includes the steps described below.

1. Visual inspection of mapped information: The site is mapped in a geographic information system (GIS) by geocoding, i.e., converting the street address to longitude and latitude coordinates. The site map is overlaid by maps of the free field strong ground motion recording stations, the location of the epicenter, and a surface geology map. If available, a topography map and a liquefaction/landslide map are included as well. Stations in the vicinity of the site (less than approximately three miles) that are on similar soil conditions as the site are selected for use in the analysis. Distances between the epicenter and the site and between the epicenter and the stations are measured in the GIS.

2. Data collection and preliminary analysis: The strong ground motion data from the recording stations identified in Step 1 are collected from public ground motion archives. The intent is to spatially interpolate the horizontal and vertical acceleration response spectra at the site, thus response spectra must be computed if they are not provided in the strong motion data sets. In addition, the data for ground motion in the horizontal direction must all be aligned in the same two orthogonal directions for all stations, thus rotation of time history data may be required prior to computing response spectra.

3. Weighted averaging: The acceleration response spectra (two horizontal and one vertical) at each station are assigned a weighting factor based on two attributes: (a) the inverse of the distance between the station and the site, and (b) a quality factor based on the analysts subjective opinion as to how well the station record represents the ground motion that actually occurred in the free field in the vicinity of the site. Reasons for a lower quality factor include the housing of the recording instrument (a small one-or two-story building as opposed to a free field instrument housing), subtle changes in topography, or unmapped geologic variations. Table 1 shows a method for quantifying subjective quality about the recording station data, which is a slightly modified version of a table provided in [5]. The weighting factors for the stations are normalized to add to 1.0. The estimate of the site-specific acceleration response spectra (two horizontal and one vertical component) is computed as a weighted average of the acceleration response spectra at the stations.

4. Correction for relative epicentral distances: The weighted average produced in Step 3 is modified to account for differences between the location of the center of mass of the stations with respect to the epicenter and the location of the site with respect to the epicenter. For example, if all stations used in the site estimate are located farther from the epicenter than the site is, it is assumed that the site estimate would be higher to some degree given the decay of ground motion intensity with distance from the epicenter. The correction for the site ground motion estimate is computed as a ratio of the spectral response values computed using an empirical attenuation relationship with the two relative distances. The

final site-specific ground motion estimate is in the form of horizontal (two orthogonal components) and vertical acceleration response spectra.

Table 1 Probability Values Corresponding to Subjective Opinions (Modified from [5])

Subjective Opinion	Single-number probability equivalent (%)	Range of equivalent probabilities (%)
Certain	100	NA
Almost certain	90	90-99.5
Very high chance	90	85-99
Very likely	85	75-90
High chance	80	80-92
Very probable	80	75-92
Very possible	80	70-87.5
Likely	70	65-85
Probable	70	60-75
Even chance	50	45-55
Medium chance	50	40-60
Possible	40	40-70
Low chance	20	10-20
Unlikely	15	10-25
Improbable	15	5-20
Very low chance	10	5-15
Very unlikely	10	2-15
Very improbable	5	1-15
Almost impossible	2	0-5
Impossible	0	NA

QUANYTIFYING CONFIDENCE IN SITE-SPECIFIC GROUND MOTION ESTIMATE

As mentioned earlier, the ground motion estimation method described in the previous section has been used for more than 50 forensic evaluations of earthquake damage from the 1994 M 6.7 Northridge earthquake. Recently, the question has arisen as to how to quantify the uncertainty or the degree of confidence in the site-specific ground motion estimate. A procedure has been developed that relies on a suite of empirical attenuation relationships that are applicable to the specific faulting mechanism and soil conditions of the site. The procedure involves the steps described below.

1. Estimate ground motion from attenuation relationships: Empirical attenuation models are selected that are applicable to the faulting mechanism of the earthquake and to the soil conditions at the site. If enough time has elapsed since the occurrence of the event, models that have been developed with inclusion of the data from the event should be selected. The ground motion (acceleration response spectrum) at the site is computed with each of the models. At least four models should be selected.

2. Select period range of interest: The fundamental period of the building under evaluation is computed using an approximate method that depends on the height and structural material (e.g., equation 30-8 in Section 1630.2.2 of the 1997 Uniform Building Code [6]) or through structural analysis using the building's structural properties and deformation characteristics. The site-specific estimate of the earthquake ground motion, computed using the four steps described above, is smoothed over the period range of interest by averaging the values at the fundamental period and at periods above and below the fundamental period. The length of the smoothing window is somewhat subjective and depends on the method used to estimate the building's fundamental period and the shape of the site-specific response

spectra in the region surrounding the estimated period. Depending on the form of the attenuation models selected in Step 1 above, smoothing of the spectra computed from the attenuation models over the period range of interest may also be required.

3. Fit probability distribution: The spectral response values at the building's fundamental period computed with the attenuation models in Step 1 above (smoothed if necessary) are used to fit a probability distribution of the spectral acceleration at the building site at the fundamental period of the building. The form of the distribution depends on the data points.

4. Estimate confidence: The confidence in the site-specific acceleration response spectra, developed according to the steps described in the previous section, is computed by evaluating how the spectral acceleration estimate at the building's fundamental period compares to the probability distribution fit in Step 3 above. Table 1 is used to relate the quantified confidence value to a subjective description of how well the site-specific ground motion estimate compares to that which would have been expected to occur at the site based on empirical attenuation models.

In the following section, an example is used to illustrate the four steps described in the previous section for estimating the site-specific strong ground motion and the four steps described above for quantifying the confidence in the site-specific estimate.

EXAMPLE APPLICATION

The example building is a hypothetical 3-story wood frame multi-family housing structure being evaluated for damage from the 1994 M 6.7 Northridge earthquake.

Estimation of Site-Specific Strong Ground Motion

The first step in the estimation of the site-specific strong ground motion is the visual inspection of mapped information. Figure 3 shows the location of the building, the earthquake's epicenter, the strong ground motion stations, and the regions of surface geology from the state site conditions map [7]. As shown in Figure 3, the site is located on a type CD soil (stiff alluvium), approximately 16.5 miles southeast of the epicenter. There are four ground motion recording stations surrounding the site, namely USC 20, USC 21, USC 91, and CGS 24303. All four stations are also on type CD soil, except stations USC 91 and CGS 24303, which border on regions of soil type D (alluvium). Table 2 and Figure 4 are the results of the second step in the process – data collection and preliminary analysis. Table 2 lists the parameters of the four ground motion stations and Figure 4 shows the acceleration response spectra in the three component directions for the four stations. The ground motion data are extracted from [8].

The third step in the ground motion estimation process is the weighted averaging. The stations are first assigned a weighting factor based on a subjective assessment of the quality of the recording, i.e., how well the recorded data at the station represents the true free field motion at the station location. The values in Table 1 are used to assign the weight. Station CGS 24303 receives a weight of 0.95, reduced from 1.0 due to the fact that it is located on the border of two surface geology types according to the map in Figure 3. Stations USC 20 and 21 receive 0.9, due to the fact that the instruments are located on the first floor of one-story buildings, and Station 91 receives a 0.85 because it's instrument is on the first floor of a two-story building and the station is located on the border of two surface geology types according to the map in Figure 1. A second weighting factor is assigned to each station based on the distance between the station and the building site to account for the decay in ground motion with distance. The distance-based weighting factors are combined with the subjective quality weighting factor and normalized to add to 1.0 for all the stations used in the analysis. The resulting weighting factors are: 0.24 for Station CGS 24303, 0.33 for Station USC 20, 0.25 for Station USC 21, and 0.18 for Station USC 91. The ground motion at the building site (acceleration response spectra in three component directions) is computed as a weighted average of the ground motion at each of the stations using these weighting factors.

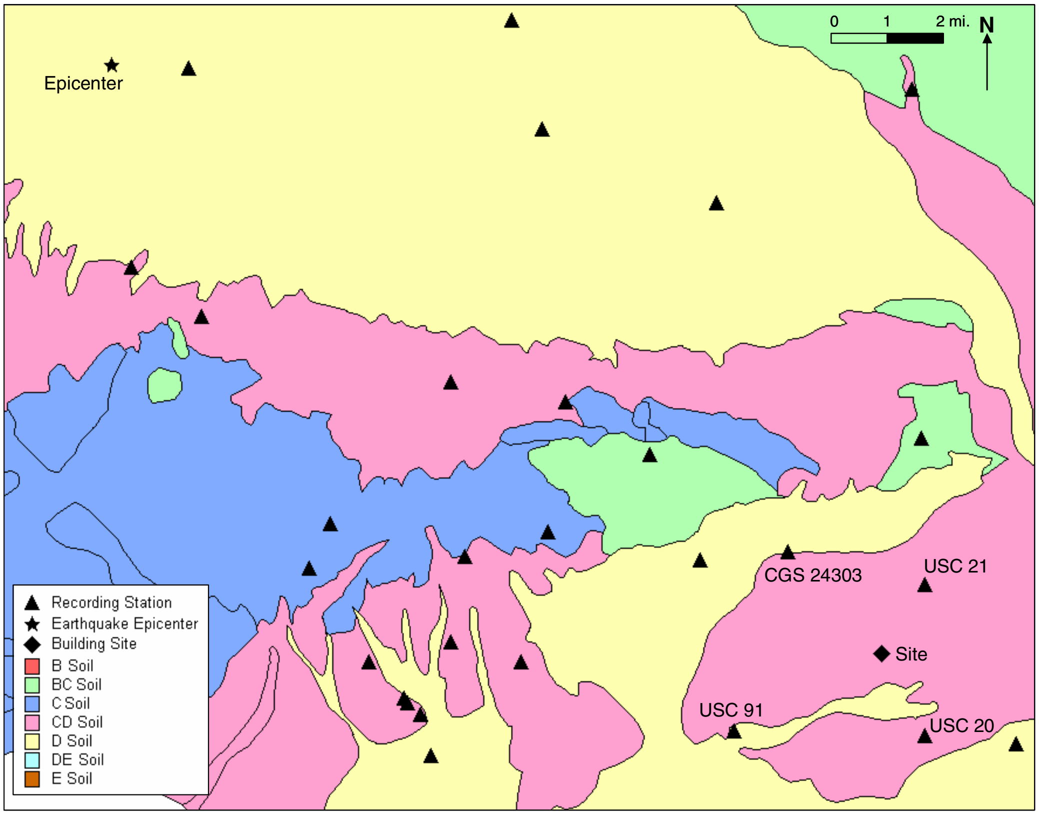

Figure 3 **Map showing location of hypothetical example building site with respect to 1994 Northridge earthquake epicenter, free field ground motion recording stations, and regions of surface geology from [7].**

The final step in the estimation of the ground motion at the building site is to adjust the weighted average ground motion to account for the attenuation of motion from the epicenter, i.e., the relative distance of the stations and the building site to the epicenter. The weighted geographic centroid of the stations is used to compute the distance of the stations to the epicenter. The empirical attenuation relationship of Sadigh et al. [10], which incorporates data from the 1994 Northridge earthquake, is used to compute the ratio of this distance to the distance between the epicenter and the building site. For this example, the ratio is computed as 0.98, and is used as a multiplier on the estimated response spectra at the building site to account for attenuation of ground motion from the epicenter to the stations and the building site. The final estimate of the site-specific ground motion for this example is shown in Figure 5. The peak ground acceleration (*PGA*) values associated with this ground motion estimate are: 0.32g in the north-south direction, 0.24g in the east-west direction, and 0.087g in the vertical direction. The effective peak acceleration (*EPA*) values are: 0.29g in the north-south direction, 0.24g in the east-west direction, and 0.071g in the vertical direction. A comparison of these results with the values shown in Table 2 shows the estimated ground motion levels fall somewhere between the ground motion recorded at Stations CGS 24303 and USC 20. The ground motions recorded at Stations USC 21 and USC 91 are somewhat higher than the site estimate, however these two stations received lower weights in the weighted averaging process, thus they have less influence on the estimate.

Table 2 Summary of Information and Parameters for Ground Motion Stations in the Vicinity of the Building Site (Data Modified from [8])

Owner and number	California Geologic Survey, CGS 24303	University of Southern California, USC 20	University of Southern California, USC 21	University of Southern California, USC 91
Address	Hollywood Storage Grounds, Los Angeles	2628 W. 15th St., Los Angeles	607 N. Westmoreland Ave., Los Angeles	5360 Saturn St., Los Angeles
Geographic coordinates	118.339 ºW, 34.090 ºN	118.298 ºW, 34.045 ºN	118.298 ºW, 34.082 ºN	118.355 ºW, 34.046 ºN
Site conditions	Stiff alluvium	Stiff alluvium	Stiff alluvium	Stiff alluvium
Distance to site	2.3 miles	1.6 miles	2.1 miles	2.8 miles
Location of instrument	Free field	Ground floor, 1 story	Ground floor, 1 story	Ground floor, 2 story
Horizontal *PGA* (N-S)[1]	0.39 g	0.17 g	0.42 g	0.41g
Horizontal *EPA* (N-S)[2]	0.35 g	0.12 g	0.40 g	0.38g
Vertical *PGA*	0.14 g	0.046 g	0.083 g	0.099g
Vertical *EPA*	0.086 g	0.053 g	0.071 g	0.088g
Horizontal *PGA* (E-W)	0.23 g	0.096 g	0.33 g	0.42g
Horizontal *EPA* (E-W)	0.22 g	0.10 g	0.35 g	0.40g
Distance to Epicenter	14.3 miles	18.0 miles	16.5 miles	15.5 miles

Notes: 1. PGA is peak ground acceleration.
2. EPA is effective peak acceleration, the average of the 5% damped acceleration response spectra over the period range of 0.1 to 0.5 seconds, divided by 2.5 [9].

Quantifying Confidence in Site-Specific Ground Motion Estimate

The first step in quantifying the confidence in the site-specific ground motion estimate is to select relevant empirical ground motion attenuation relationships and compute the motion (mean or median value of horizontal spectral acceleration) that would have been expected to occur at the site during the earthquake. For this example, five empirical ground motion attenuation relationships are selected that are applicable to shallow crustal earthquakes with normal or thrust faulting, alluvial soil conditions, and magnitudes in the range of the 6 to 7. The relationships are as follows.

- Abrahamson and Silva, 1997 [11]
- Boore, Joyner, and Fumal, 1997 [12]
- Campbell, 1997 [13]
- Sadigh et al., 1997 [10]
- Spudich et al., 1999 [14]

Figure 6 shows the plot of the horizontal acceleration response spectra at the site predicted by the five attenuation relationships listed above.

The second step in quantifying confidence is to estimate the period range of interest. The fundamental period of the building (T, in seconds) is estimated from the following formula given in the 1997 Uniform Building Code [6]:

$$T = C_t\,(h_n)^{3/4} \tag{1}$$

where:

C_t = 0.02 for wood frame buildings, and

h_n = height of the building in feet (taken as 30 feet for this example).

Using Equation 1, the fundamental period of the building is estimated as 0.26 seconds. At a period of 0.26 seconds, the horizontal spectral acceleration values predicted by the five empirical attenuation relationships are: 0.31g, 0.44g, 0.34g, 0.43g, and 0.30g. These become the five data points through which a probability distribution will be fit in the third step of the process. The site-specific ground motion (Figure 5) at a period of 0.26 seconds is estimated as 0.67g, computed as the average of the motion in the two orthogonal horizontal directions and smoothing over a period window of 0.04 seconds.

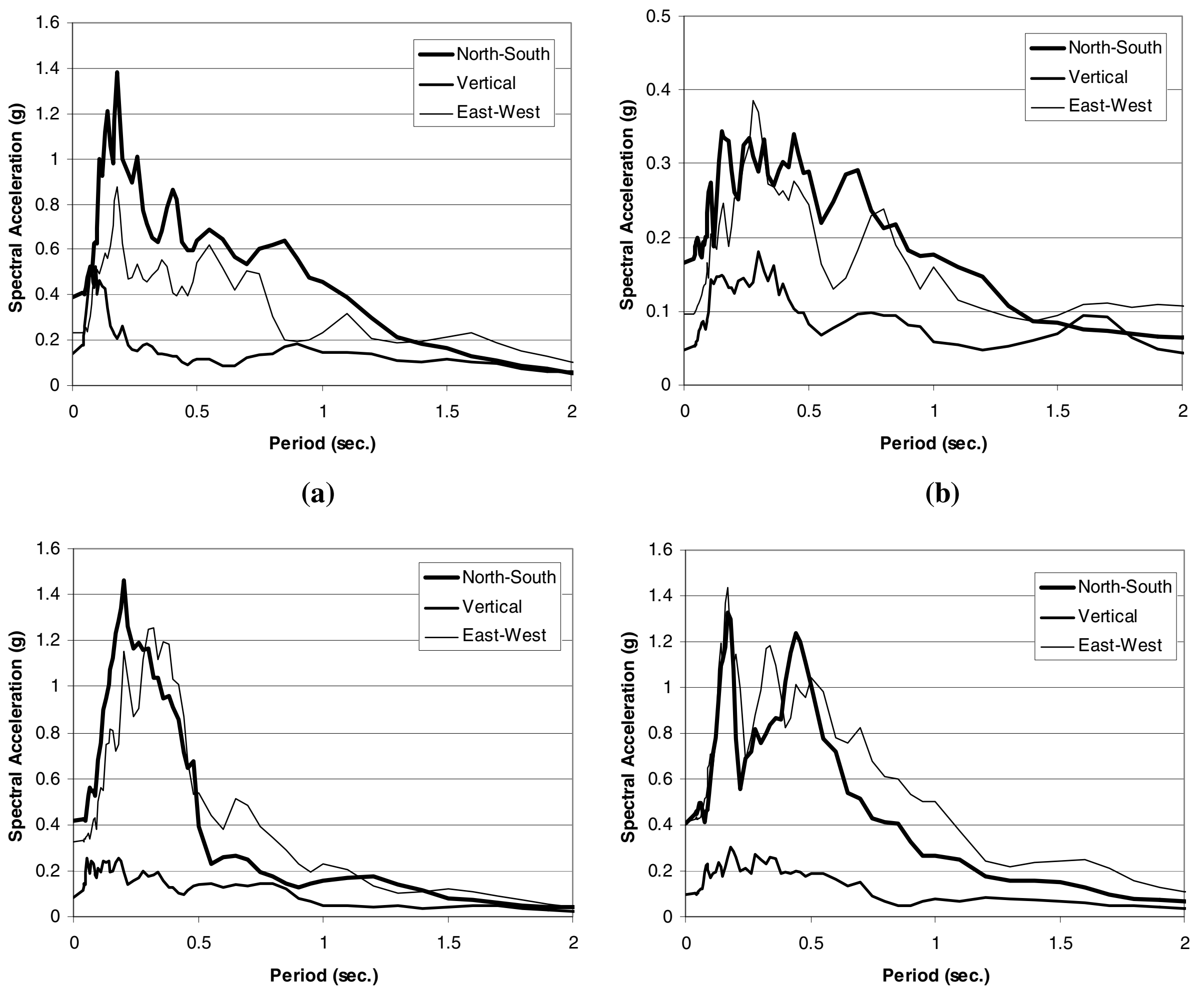

Figure 4 **Acceleration response spectra for four stations surrounding building site: (a) CGS 24303, (b) USC 20, (c) USC 21, and (d) USC 91.**

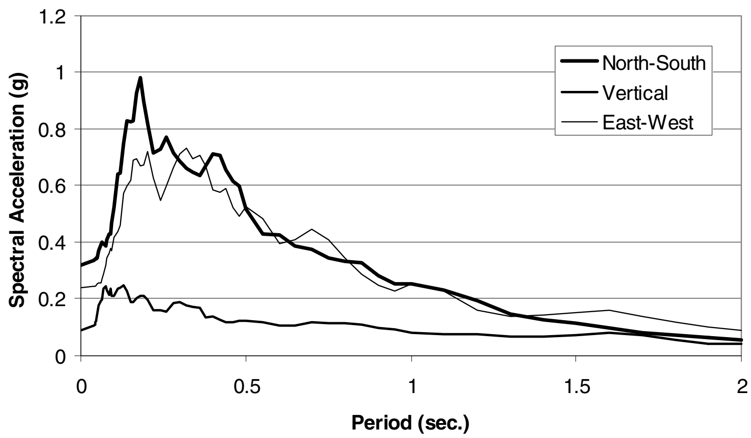

Figure 5 Estimate of site-specific acceleration response spectra for 1994 Northridge earthquake at hypothetical example building site.

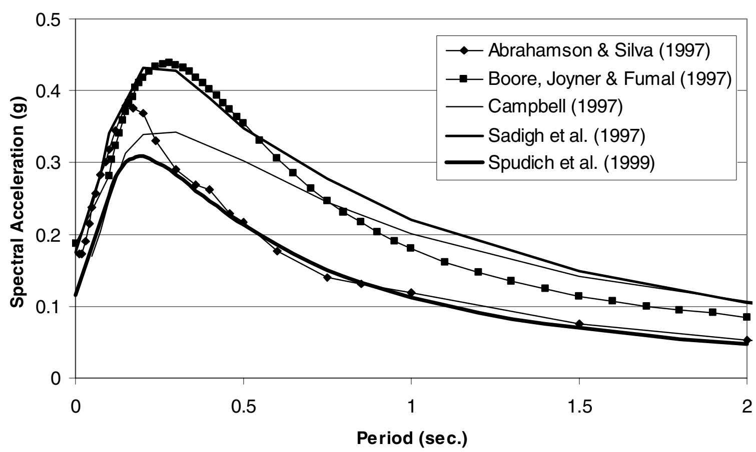

Figure 6 Horizontal acceleration response spectra at the site predicted by five attenuation relationships.

The third step in the process to quantify confidence is to develop a probability distribution based on the data points of ground motion at the site estimated from the empirical attenuation relationships. For simplicity in this example, a normal distribution is used with the distribution mean and standard deviation set equal to the sample mean and standard deviation. The mean is computed as 0.37g with a standard deviation of 0.067g. Figure 7 shows the normal distribution corresponding to these two parameters.

The final step in quantifying the confidence in the site estimate of the earthquake ground motion is to compare the estimate value, 0.60g as indicated above, to the distribution fit to the empirical attenuation values, as shown in Figure 7. For this example, the ground motion at the site estimated from the recorded motion at nearby stations is significantly higher than that which is predicted by the five empirical attenuation relationships used in the analysis. Given the normal probability distribution shown in Figure 7, the probability that the spectral acceleration at a period of 0.26 seconds exceeds a value of 0.67g is approximately 0.3%. Thus prior to the earthquake, there is an approximately 99.7% probability that the spectral acceleration at the site would not exceed 0.67g. This illustrates that the ground motions generated by the earthquake are near the upper bound of the range of values estimated with empirical attenuation, and a more meaningful comparison would be with this higher level (upper bound) rather than the mean or median values.

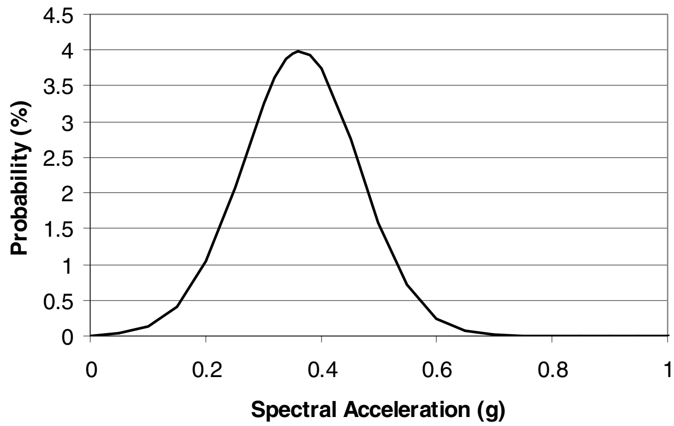

Figure 7 **Normal distribution fit to data points (horizontal acceleration response spectral value at 0.26 seconds) estimated from empirical attenuation relationships.**

By computing the standard error terms associated with each of the five attenuation relationships at a period of 0.26 seconds, the approximate upper bound spectral acceleration values can be computed and used to fit a new distribution. Figure 8 shows the normal distribution fit to the five data points corresponding to the approximate upper bound values of the empirical attenuation relationships. Comparison of the site estimate of the 0.26 second spectral acceleration computed from the weighted average of the recorded data (0.67g) with the distribution in Figure 8 indicates that the recorded motion in the earthquake near the site does indeed correspond to the upper bound of the range of values predicted by empirical attenuation. The normal distribution shown in Figure 8 has a mean of 0.61 and a standard deviation of 0.073, thus the site estimate value falls within one standard deviation of the mean. Given this distribution, the probability that the spectral acceleration at a period of 0.26 seconds exceeds a value of 0.67g is approximately 20%, or there would be an approximately 80% probability that the spectral acceleration at the site is less than or equal to 0.67g.

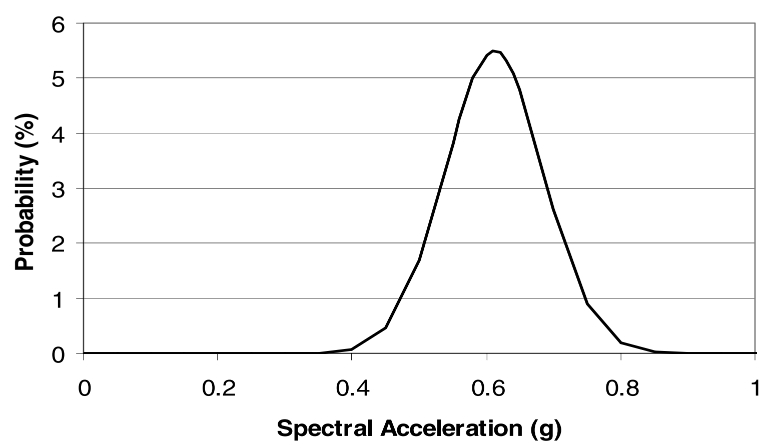

Figure 8 **Normal distribution fit to data points (approximate upper bound horizontal acceleration response spectral value at 0.26 seconds) estimated from empirical attenuation relationships.**

The probability estimates of 20% or 80% computed above do not answer the question about how confident the analyst is in the ground motion estimate of 0.67g, assuming that the ground motion that would have been expected is normally distributed with a mean of 0.61g. Intuitively, based on the relatively small difference of 0.06g (0.67g-0.61g), one would consider the estimate to have a somewhat high level of confidence. An example quantified measure of this confidence can be related to the percent error in the site estimate compared to the distribution mean, computed as 100% × 0.06g ÷ 0.61g = 9.5%. Confidence can be approximated as 100% minus the percent error or 90.5% for this example. Using this value with the information in Table 1, the analyst would be almost certain or conclude there is a very high chance that the ground motion estimated from the weighted average approach is that which actually occurred in the earthquake at the building site. (For comparison purposes, following this same quantification using the earlier distribution mean of 0.37g results in a confidence of 16%, which according to Table 1 indicates that the ground motion estimate of 0.67g is unlikely or improbable.)

Although the quantification of confidence computed from the comparison of the estimate to the distribution mean is relatively straightforward, it does not incorporate the uncertainty in the distribution. For this example, the estimate is nearly one standard deviation away from the mean of the distribution. This would not typically be associated with a 90% level of confidence or a subjective opinion of being almost certain the estimate is accurate. A parameter for measuring the uncertainty (or dispersion) in the distribution is the coefficient of variation (COV), or the ratio of the standard deviation to the mean. For this example, the COV is computed as .12 (0.073g ÷ 0.61g), which is relatively small and corresponds to a narrow distribution. The COV should be a consideration, in addition to the mean as discussed above, in assigning a level of confidence to the site ground motion estimate. In this example, the analyst may choose to reduce the level of confidence to 80% to account for the fact that although the estimate is close to the mean of the distribution, given the narrowness of the distribution, the estimate has a relatively larger error than computed. Using Table 1, the 80% confidence would correspond to a subjective opinion of very probable, very possible, or a high chance that the site-specific ground motion estimate is accurate.

CONCLUSIONS

This paper presents a method for the post-event estimation of site-specific strong ground motion (in the form of acceleration response spectra in the vertical and two horizontal directions) using a weighted average spatial interpolation process. The four main steps in the method are described and an example is used to illustrate the process.

In addition to the estimation of the site-specific ground motion, a method is presented for quantifying the level of confidence in the ground motion estimate, or assessing how well the estimate represents the actual ground motion that occurred at the building site. The confidence quantification method relies on empirical attenuation relationships. A probability distribution is fit to the spectral acceleration values computed from the applicable attenuation relationships at the fundamental period of the building. The site estimate is compared to the mean of the distribution and the percent error between the two values is used to quantify confidence. The measure of dispersion in the distribution is also used in the method. The four main steps in the method are described and an example is used to illustrate the process

A key assumption in the method to quantify confidence in the site estimate is that the derived distribution represents the actual ground motion at the site, and the estimate represents an experimental data point for which one would like to compute the error with respect to the actual value. The authors recognize the problems associated with this assumption and are currently working on alternative methods for quantifying confidence, for example through a Bayesian approach. In this approach, the distribution derived from empirical attenuation relationships is the prior distribution, and the recorded ground motion data are observations to update the prior distribution and produce a posterior distribution on the ground motion at the site.

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