THE PROBLEM OF THE RANDOM EARTHQUAKE IN SEISMIC HAZARD ANALYSIS: WASATCH FRONT REGION, UTAH

JAMES C. PECHMANN AND WALTER J. ARABASZ

ABSTRACT

The State of Utah's rules for dam safety require that an "Operating Basis Earthquake" (OBE) be determined for all dams within seismic zones 2 and 3 of the Uniform Building Code. The OBE is described as the earthquake with a return interval of at least 200 yrs that has the greatest potential to cause damage at the site, considering all active earthquake sources which could affect it. Previous studies have shown that at most sites in the Wasatch Front region, the dominant sources of seismic hazard for 200-yr return periods are moderate-sized earthquakes of $M_L \leq 6.5$. This result suggests that an earthquake in this size range would be an appropriate OBE for a Wasatch Front region dam. Because such earthquakes are below the usual threshold of surface faulting, their locations and magnitudes cannot easily be predicted. Hence, in seismic hazard evaluations, these moderate-sized earthquakes are usually assumed to occur randomly throughout the region. This randomness complicates the task of selecting a specific OBE for use in engineering design purposes.

We evaluate an approach to the problem of selecting an OBE which employs the concept of the "probabilistic epicentral distance" ($r_0$) introduced in the 1980's by C.K. Wood and D.A. Ostenaa of the U.S. Bureau of Reclamation. In the application considered here, $r_0$ is the radius of a circle within which the annual probability of an earthquake of $5.5 \leq M_L \leq 6.5$ is equal to some specified small number. Using an average rate of occurrence of earthquakes in this size range estimated from historical and instrumental seismicity data for the Wasatch Front region, it is found that $r_0 = 85, 58, 38, 17$ km for annual probabilities (inverse return periods) of 1/95, 1/200, 1/475, and 1/2373, respectively. Based on these distances, the calculated median magnitude of 5.8, and (for example) the Boore and others (1993) attenuation relation for peak horizontal acceleration (PHA), we calculate that the expected PHA's are, respectively, 0.04, 0.05, 0.07, and 0.13 g. These PHA's are similar to those obtained for the same annual probabilities from a simple probabilistic seismic hazard analysis in which only random earthquakes of $5.5 \leq M_L \leq 6.5$ (at distances of up to 100 km) are considered and the uncertainties in the peak accelerations predicted by the attenuation relation are ignored. However, they are factors of 1.5 to 5.7 lower than values obtained from more complete probabilistic hazard analyses for the Wasatch Front region, which take into account smaller and larger potential earthquakes and also the uncertainties in the predicted PHA's. Thus, at least in this region, the probabilistic distance method yields an OBE which significantly under-represents the ground shaking hazard. We suggest an alternative and more conservative approach to the problem of selecting an OBE which involves the direct use of results from a regional or site-specific probabilistic seismic hazard analysis.

INTRODUCTION

This paper was motivated by recent interactions with consultants engaged in seismic hazard analyses for dams in the Wasatch Front region of Utah. These consultants were facing a problem which is not unique either to the Wasatch Front region or to the seismic hazard analysis of dams. We consider the general problem here in a local context using seismic hazard analysis of dams as an example. The problem is as follows.

The State of Utah requires that deterministic seismic hazard analyses be performed for all new dams in the state located within seismic zones 2 and 3 as defined in the 1988 edition of the Uniform Building Code. On a priority basis, the State is also requiring such analyses for existing high- and moderate-hazard dams in these two zones. These zones cover more than two-thirds of Utah and encompass nearly all of the area shown in figure 1 which, following Arabasz and others (1980, 1992), we will refer to herein as the Wasatch Front region. The requirements for the seismic hazard analyses include determination of an "Operating Basis Earthquake" or OBE. Utah's statutory definition of an OBE for

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1 Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah 84112-1183
Figure 1. Epicenters of \( M_L \geq 3.0 \) independent main shocks from July 1, 1962, through December 31, 1994 (circles), and five earlier main shocks (squares) used to model earthquake recurrence in the Wasatch Front region. The solid lines are Quaternary fault traces from Witkind (1975), Gibbons and Dickey (1983), and Hecker (1993). The labeled fault segments shown by heavy lines (see table 5 for key) are those that we used for probabilistic calculations of ground-shaking hazard at a site in the Salt Lake Valley (star). The dashed boxes in the southeastern part of the map indicate areas of mining-induced seismicity in which all events were excluded from the recurrence analysis.
dam safety purposes (Morgan and Hall, 1993) requires considering "all active sources of seismicity with the potential to impact the stability of a dam" and assigning to each source an "operating basis seismic event" having a return interval of at least 200 years. Of these, the event with the greatest potential to cause damage at the site is defined as the OBE.

Previous studies have shown that at most sites in the Wasatch Front region, spatially "random" or "background" earthquakes of M ≤ 6.5 are the dominant sources of seismic hazard for relatively short return periods such as 200 years (Youngs and others, 1987; Arabasz and others, 1992; Wong and others, 1995). Thus, for most dams in this region, the appropriate choice for an OBE would be an earthquake of this type. The term "random earthquake" comes from the observation that earthquakes in this size range in the Basin and Range Province usually have little or no surface rupture, and often occur on buried faults with no clear surface expression (Doser, 1985; Arabasz and others, 1992; dePolo, 1994). Thus, for the purposes of seismic hazard evaluations in this region, it is usually assumed that such earthquakes can occur at any random location.

The treatment of random earthquakes presents a problem in deterministic seismic hazard analyses in which a worst-case scenario is not called for. Because random earthquakes may not occur on known faults, there are no geological constraints on their possible locations and sizes other than their maximum magnitude. Without such constraints, how does one select a magnitude and distance for a design earthquake such as an OBE for a dam? One technique which has been used to guide such decisions in Utah and elsewhere is the method of probabilistic epicentral distances, which was developed during the early 1980's by C.K. Wood and D.A. Ostenaa of the U.S. Bureau of Reclamation (USBR; C.K. Wood, personal communication, 1995). This method provides a means to calculate, in effect, a minimum distance at which a random earthquake in a specified magnitude range is likely to occur at some specified level of probability.

In the first section of this paper, we review the probabilistic epicentral distance method as described by Wood and Ostenaa (1984) and derive an alternative, simpler form of their basic equation. We then evaluate the probabilistic distance method by comparing expected peak horizontal accelerations (PHA's) for design earthquakes determined by this method to PHA's determined from standard probabilistic seismic hazard assessments. From these comparisons, we conclude that the probabilistic distance method yields design accelerations similar to those calculated from a probabilistic seismic hazard assessment for the random earthquake source—when the same magnitude range is considered for both and the uncertainty in the PHA's predicted by the attenuation relation is ignored. However, in the form in which it is usually used, the probabilistic distance method underestimates the ground-shaking hazard in the Wasatch Front region at any given level of probability. The primary reason for this underestimation is that a wide range of earthquake magnitudes contributes significantly to the ground-shaking hazard in the Wasatch Front region, even at relatively short return periods.

THE PROBABILISTIC DISTANCE METHOD

Wood and Ostenaa (1984) define probabilistic epicentral distance, r₀, as the radius of a circle within which the probability of an earthquake in the magnitude interval M ± ΔM/2 during time t is equal to some specified value P. For engineering applications, P is usually chosen to be small. To derive an equation for r₀, Wood and Ostenaa assume that earthquake probabilities are spatially uniform in the region of interest and can be adequately described by the Poisson distribution, which is commonly used to model earthquake occurrence. In a Poisson process, the events occur independently at an average rate which does not vary with time. Under these assumptions, they obtain the following equation for r₀:

\[ r₀ = \sqrt{\left[ \frac{-\ln(1-P)}{\pi \cdot t} \right] \frac{10^{-a' + bM}}{10^{bΔM/2} - 10^{-bΔM/2}}} \]  (1)

Here, a' and b are regionally-varying constants in the well-known Gutenberg-Richter frequency-magnitude relation:

\[ \log_{10} N'(M) = a' - bM \]  (2)

where N(M) is the number of earthquakes per year per unit area of magnitude M or larger. The primes denote the normalization with respect to area. To obtain the parameters for a design earthquake from this method, an appropriate magnitude interval, M ± ΔM/2, and a suitably conservative probability of occurrence, P, over time t are assumed. Equation 1 then gives the distance from the site at which the design earthquake should be placed.

There are some practical problems with the form of the probabilistic distance equation given in (1). First, the direct incorporation of the Gutenberg-Richter relation into this equation makes it more restrictive and cumbersome than is necessary. As will be shown below, r₀ can be calculated directly from the spatially normalized frequency of occurrence of events in the magnitude range of interest; one does not actually need to know the parameters a' and b of the Gutenberg-Richter relation. Also, equation (1) cannot be used to calculate r₀ values for an open-ended magnitude range, as was done, for example, for earthquakes of M ≥ 6.0 by Sullivan and others (1988) of the USBR in their seismotectonic study of central Utah. Sullivan and others (1988)
include Wood and Ostenaa's derivation of equation (1) as an appendix to their report, and reference it for the details of their methodology. However, it is not possible to reproduce their probabilistic distance calculations using this particular form of the equation because the magnitude range is specified in terms of M and ΔM and not in terms of an upper and lower limit.

A more serious problem with equation (1) is that the appropriate magnitude interval, ΔM, to use for the calculation is not at all obvious. However, the result is quite sensitive to the interval chosen. In fact, one can obtain arbitrarily large r0 values by using arbitrarily small values of ΔM. Thus, there is some potential for misuse of the probabilistic distance method. Our understanding is that this method is usually applied using magnitude intervals of 0.5 to 1.0 units, but the choice of the interval is rather arbitrary. We show below that the relatively limited magnitude range of the earthquakes generally considered in applications of the probabilistic distance method can lead to underestimation of the ground-shaking hazard.

To remedy some of the limitations of equation (1) mentioned above, we derive a simpler and more versatile form of this equation using the same assumptions made by Wood and Ostenaa (1984). We set t = 1 yr and consider a magnitude interval M1 ≤ M < M2. Then becomes the annual probability of one or more earthquakes of M1 ≤ M < M2 occurring in a circular area of radius r0. Let λ be the average annual rate of occurrence of events in this magnitude range within the circle. Then, according to the Poisson model,

\[ P = 1 - e^{-\lambda}. \] (3)

We define \( n'(M_1, M_2) \) as the average number of earthquakes of M1 ≤ M < M2 per year per unit area. Then,

\[ \lambda = \pi r_0^2 n'(M_1, M_2). \] (4)

Substituting (4) into (3) and solving for r0 gives

\[ r_0 = \left( \frac{-\ln(1-P)}{\pi n'(M_1, M_2)} \right)^{1/2} \] (5)

This equation gives the radius of a circle within which the annual probability of an earthquake of M1 ≤ M < M2 equals P. Thus, an earthquake in this magnitude range has an annual probability P of occurring at a distance closer than r0, the probabilistic epicentral distance.

Although \( n'(M_1, M_2) \) can be determined by any suitable method, the best estimate is generally one calculated using a Gutenberg-Richter-type frequency-magnitude relation (2) for the region of interest:

\[ n'(M_1, M_2) = N'(M_1) - N'(M_2) \] (6)

or, similarly, using one of the alternative forms of the frequency-magnitude relation given in (7) and (8) below. Note that equation (1) with t = 1 can be obtained by setting M1 = M - ΔM and M2 = M + ΔM in (6) and using (2) to obtain an expression for \( n'(M_1, M_2) \) for substitution into (5). However, the combination of (5) and (6) is more general than (1) because recurrence relations of forms other than (2) can be used and M2 can be set equal to infinity to calculate r0 for an open-ended magnitude range.

In the following section, we model seismicity in the Wasatch Front region with a modified version of (2) for subsequent use in applying the probabilistic distance method to this region.

**RECURRENTNESS MODELING**

For this analysis, we revised and updated our earlier modeling of earthquake recurrence in the Wasatch Front region, which was described in Arabasz and others (1992). The primary changes from our earlier work are (1) the use of a longer instrumental earthquake catalog, extending from July 1962, when the University of Utah regional seismic network began operating, through December 1994; (2) incorporation of "historical" (primarily non-instrumental) earthquake data for larger earthquakes from 1900 to 1962; and (3) the use of a different methodology to remove aftershocks and other dependent events from the catalog.

In this study, we use the modified form of the Gutenberg-Richter relation (equation (2)) proposed by Cornell and Van Marke (1969; see also Youngs and Coppersmith, 1985). If A is defined as the average number of events per year of M ≥ 3.0 in the region of interest (that is, A = N(3.0) = 10^{a(M-3.0)}; note that the primes on "N" and "a" have been dropped along with the normalization for area), then the Gutenberg-Richter equation can be rewritten in shifted exponential form as

\[ N(M) = A10^{-b(M-3.0)} \] (7)

where N(M) is the cumulative number of earthquakes per year of magnitude M and greater in the region. Since it is generally accepted that there is a limit on the size of earthquakes possible in any given region, which we designate Mmax, then it is appropriate to modify equation (7) by subtracting the predicted rate of occurrence of earthquakes with M ≥ Mmax, N(Mmax), from N(M), and then multiplying by a normalization factor to preserve the meaning of A:
Table 1. Completeness intervals and counts of earthquakes used in recurrence modeling

<table>
<thead>
<tr>
<th>Magnitude range</th>
<th>Completeness period</th>
<th>Interval (yr)</th>
<th>Number from non-instrumental data</th>
<th>Total number of earthquakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 ≤ M&lt;sub&gt;L&lt;/sub&gt; &lt; 3.5</td>
<td>Jul 1962 – Dec 1994</td>
<td>32.5</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>3.5 ≤ M&lt;sub&gt;L&lt;/sub&gt; &lt; 4.0</td>
<td>Jul 1962 – Dec 1994</td>
<td>32.5</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>4.0 ≤ M&lt;sub&gt;L&lt;/sub&gt; &lt; 4.67</td>
<td>Jul 1962 – Dec 1994</td>
<td>32.5</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>4.67 ≤ M&lt;sub&gt;L&lt;/sub&gt; &lt; 5.33</td>
<td>Jan 1950 – Dec 1994</td>
<td>45.0</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>5.33 ≤ M&lt;sub&gt;L&lt;/sub&gt; &lt; 6.0</td>
<td>Jan 1938 – Dec 1994</td>
<td>57.0</td>
<td>0</td>
<td>1&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>6.0 ≤ M&lt;sub&gt;L&lt;/sub&gt; &lt; 6.67</td>
<td>Jan 1900 – Dec 1994</td>
<td>95.0</td>
<td>1</td>
<td>3&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>1</sup> See Table 1 of Arabasz and others (1992) for a listing identifying these earthquakes. The largest one, and the only pre-July 1962 earthquake we used for which instrumental size measurements are available, is the 1934 M<sub>W</sub> 6.6 Hansel Valley, Utah, earthquake (Doser, 1989).

\[
N(M) = A \frac{10^{-b(M-3.0)} - 10^{-b(M_{\text{max}}-3.0)}}{1 - 10^{-b(M_{\text{max}}-3.0)}} \quad (8)
\]

To model the frequency of earthquake occurrence in the Wasatch Front region, we fit equation (8) to observed rates of earthquake activity (table 1) using an assumed M<sub>max</sub> of 7.75 (discussed below and in Arabasz and others, 1992) and the same algorithm used by Youngs and others (1987). This algorithm applies the maximum likelihood method of Weichert (1980) for variable periods of completeness, generalized to allow for variable magnitude intervals. In our previous modeling (Arabasz and others, 1992), we also used the method of Weichert (1980) to fit data with a shifted and truncated exponential distribution of the form of equation (8). However, we presented the results in the form of the original Gutenberg-Richter relation (equations (2) and (7)) because the effect of the assumed M<sub>max</sub> of 7.5 was negligible over the magnitude range of the data (M<sub>L</sub> 3.0 to 6.0).

The data for our recurrence modeling come primarily from the University of Utah instrumental earthquake catalog, which begins in July 1962 (see Arabasz, 1979; Richins, 1979; and Arabasz and others, 1980, 1992). The magnitudes in this catalog are either direct or indirect estimates of Richter or local magnitude, M<sub>L</sub>. To obtain more robust estimates of recurrence rates for larger, less frequent earthquakes, we supplemented the data in the instrumental catalog with pre-1962 data from the University of Utah historical earthquake catalog (Arabasz and McKee, 1979). The magnitudes for most of the earthquakes in the historical catalog are estimated from maximum Modified Mercalli intensity, I<sub>o</sub>, assuming the Gutenberg and Richter (1956) relationship

\[
M_L = \frac{2}{3} I_o + 1, \quad (9)
\]

as justified for Utah by the U.S. Geological Survey (1976). Based on earlier analyses of completeness thresholds in Utah's earthquake record (U.S. Geological Survey, 1976; Arabasz and others, 1980; Youngs and others, 1987), we adopted the following conservative thresholds of completeness for the Wasatch Front region: M<sub>L</sub> ≥ 3.0 since July 1962; M<sub>L</sub> ≥ 4.3 (I<sub>o</sub> ≥ V) since January 1950; M<sub>L</sub> ≥ 5.0 (I<sub>o</sub> ≥ VI) since January 1938; and M<sub>L</sub> ≥ 5.7 (I<sub>o</sub> ≥ VII) since January 1900. The 1938 and 1950 dates correspond to key milestones in the systematic receipt and processing of regional earthquake data for the Utah region by the former U.S. Coast and Geodetic Survey (see Arabasz, 1979).

Most methods of seismic hazard analysis, including those used in this paper, require estimates of recurrence rates for independent main shocks only. To obtain such estimates, it was necessary for us to remove dependent events such as aftershocks, foreshocks, and secondary events in swarm sequences from the University of Utah catalog before proceeding with the recurrence modeling. It was also necessary for us to remove seismic events from two parts of the study area (dashed boxes, figure 1) where the seismicity is predominantly mining-related (see Williams and Arabasz, 1989; Wong and others, 1989). The process of removing naturally occurring dependent events from an earthquake catalog is commonly referred to as "declustering" because of the tendency of dependent events to cluster in space and time. Some available methods for identifying dependent events include the use of: (i) empirical time and distance windows, which generally vary with main shock magnitude (e.g., Youngs and others, 1987); (ii) statistical tests for space-time windows that have seismicity rates significantly higher...
than the local background rates (e.g., Veneziano and Van Dyck, 1985, 1986; Shimizu, 1987); and (iii) physical models which predict time-varying spatial windows within which a main shock is expected to influence the occurrence of dependent events (e.g., Reasenberg, 1985).

In our earlier recurrence modeling (Arabasz and others, 1992), we relied on declustering results based on technique (ii) obtained by Shimizu (1987) for Utah's instrumental catalog from July 1962 through December 1985. The algorithm used by Shimizu (1987) was unavailable for application to our extended catalog, so we applied technique (iii) in the form of the widely-used algorithm of Reasenberg (1985), modified to account for characteristics of aftershock behavior in the Utah region (Arabasz and Hill, 1994). Specifically, we incorporated the following generic Omori parameters (cf. Reasenberg and Jones, 1989, for California): \( a = -2.31, b = 0.87, p = 0.75, \) and \( c = 0.02. \) The declustering parameters, in the notation of Savage and dePolo (1993), were: \( Q = 20, \tau_{\text{min}} = 1 \) d, \( \tau_{\text{O}} = 20 \) d, and \( \tau_{\text{max}} = 100 \) d. The output of Reasenberg's computer program was modified for our purposes here to list the actual catalog magnitude and location of the independent events identified, instead of "equivalent" values for each cluster. To test our declustering results, we compared our list of 61 \( M \geq 3.0 \) independent events from 1962 to 1985 with the list of 59 such events identified by Shimizu (1987) and found very good agreement, with 57 events common to both lists.

Table 1 lists our counts of independent main shocks for six magnitude bins selected to minimize the effects of uncertainties in the non-instrumental magnitude estimates. The completeness period listed for each bin applies to its entire magnitude range. From these counts and the methodology described above, we obtained the following parameters for equation (8) with \( M_{\text{max}} = 7.75: \)

\[
A = 3.2 \pm 0.3 \quad \text{and} \quad b = 0.72 \pm 0.06.
\]

The uncertainty limits represent one standard error. Substituting these parameters into equation (8) gives

\[
N(M_L) = (3.2 \pm 0.3)10^{(-0.72 \pm 0.06)(M_L - 3.0)}
\]

\[
-1.2 \pm 1.4 \times 10^{-3}
\]

Note that to calculate the upper-bound uncertainty limits for \( N(M_L) \), the error values should be consistently added in this equation and to calculate the lower bounds, they should be subtracted. Figure 2 shows a plot of equation (8) with these parameters together with the earthquake activity rates computed from table 1. Recurrence intervals calculated using equation (10) are tabulated in table 2.

The results of our recurrence analysis (equation (10), table 2) do not differ greatly from our earlier results (Arabasz and others, 1992). Our new b-value of 0.72 \pm 0.06 is nearly identical to our old b-value of 0.71 \pm 0.09. Our new A-value of 3.2 \pm 0.3 is somewhat higher than our previously-
determined value of 2.51, but should be more accurate because it is derived from a longer time sample. Other comparisons indicate that the recurrence parameters of equation (10) are stable. For example, using only instrumental earthquake data from 1962 to 1994 for the Wasatch Front region,
we obtain \( A = 3.2 \pm 0.3 \) and \( b = 0.73 \pm 0.08 \). Similar analyses for the entire Utah region yield a \( b \)-value of \( 0.78 \pm 0.04 \) when historical data are included and \( 0.79 \pm 0.05 \) when only instrumental data for 1962 to 1994 are used. (A-values for the Wasatch Front and Utah regions obviously differ because of the different areas involved.)

Although our recurrence model is based chiefly on local magnitude, \( M_L \), it may be considered equivalent to moment magnitude, \( M_W \), for the following reasons. First, the \( M_L \) magnitude scale is virtually identical to the \( M_W \) scale up to about magnitude 6.5 (Kanamori, 1983, figure 4). Second, instrumental \( M_W \) determinations available for two of the three largest earthquakes counted here (see Smith and Arabasz, 1991, for references) agree very well with the catalog magnitudes we used and confirm the placement of these earthquakes in our highest magnitude bin. Third, our selection of an upper-bound magnitude for our recurrence model was made in terms of \( M_W \), with allowance for an uncertainty of 0.25 magnitude unit (e.g., Youngs and others, 1987) above an expected \( M_{\text{max}} \) value of 7.5.

Table 2. Average recurrence intervals for earthquakes in the Wasatch Front region

<table>
<thead>
<tr>
<th>Magnitude range</th>
<th>Average recurrence interval(^\text{2})(yr)</th>
<th>Preferred estimate(^\text{2})</th>
<th>Range of estimates(^\text{3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_L \geq 3.0 )</td>
<td>0.31</td>
<td>0.29 - 0.34</td>
<td></td>
</tr>
<tr>
<td>( M_L \geq 3.5 )</td>
<td>0.72</td>
<td>0.61 - 0.85</td>
<td></td>
</tr>
<tr>
<td>( M_L \geq 4.0 )</td>
<td>1.6</td>
<td>1.3 - 2.1</td>
<td></td>
</tr>
<tr>
<td>( M_L \geq 4.5 )</td>
<td>3.8</td>
<td>2.8 - 5.1</td>
<td></td>
</tr>
<tr>
<td>( M_L \geq 5.0 )</td>
<td>8.7</td>
<td>6.1 - 12.6</td>
<td></td>
</tr>
<tr>
<td>( M_L \geq 5.5 )</td>
<td>20</td>
<td>13 - 31</td>
<td></td>
</tr>
<tr>
<td>( M_L \geq 6.0 )</td>
<td>48</td>
<td>29 - 79</td>
<td></td>
</tr>
<tr>
<td>( M_L \geq 6.5 )</td>
<td>120</td>
<td>70 - 210</td>
<td></td>
</tr>
<tr>
<td>( 3.5 \leq M_L &lt; 4.5 )</td>
<td>0.88</td>
<td>0.78 - 1.0</td>
<td></td>
</tr>
<tr>
<td>( 4.5 \leq M_L &lt; 5.5 )</td>
<td>4.6</td>
<td>3.6 - 6.1</td>
<td></td>
</tr>
<tr>
<td>( 5.5 \leq M_L &lt; 6.5 )</td>
<td>24</td>
<td>16 - 37</td>
<td></td>
</tr>
</tbody>
</table>

\(^\text{1}\)\(38^\circ 55' \text{N} - 42^\circ 30' \text{N}, 110^\circ 25' \text{W} - 113^\circ 10' \text{W}, \) excluding mining-related seismicity in the southeastern part of the study area. Net sample area equals 86,800 km\(^2\).

\(^\text{2}\)Calculated using the best-fit \( A \) and \( b \) values of 3.2 and 0.72, respectively, and a maximum magnitude of 7.75.

\(^\text{3}\)Range allowing for one-standard-error variations in the recurrence parameters: \( A = 3.2 \pm 0.3 \) and \( b = 0.72 \pm 0.06 \).

Given the validity of the recurrence model of figure 2 for \( M_W \), we have superposed for comparison the annualized frequency of surface-faulting earthquakes throughout the Wasatch Front region during the last 15,000 years estimated by Hecker (1993). Because the recurrence curve is for cumulative annual frequency, the appropriate position on the magnitude axis to plot her estimate is at the lower end of the \( M_W \) range represented in her tabulation. We estimate the minimum magnitude for the surface-faulting earthquakes in Hecker's tabulation to be \( M_W 6.5 \) to 7.0. This estimate is based on the threshold of surface faulting and an estimated minimum detectable average displacement of 0.5 to 1.0 m (based, in part, on Schwartz and Coppersmith, 1984), which translates to a minimum \( M_W \) of 6.6 to 6.9 using the empirical relations of Wells and Coppersmith (1994). Figure 2 shows excellent agreement between the geologically-determined rate of prehistoric surface-faulting earthquakes in the Wasatch Front region and the rate predicted by an extrapolation of our recurrence relation beyond the effective magnitude limits of the data used to determine it. Hecker (1993) noted a similar agreement between geological and instrumental estimates of earthquake rates using our 1992 recurrence relation. This agreement suggests that the average frequency of earthquakes in the Wasatch Front region during the last three to nine decades has been representative of the average frequency during the last 15,000 years.

**PROBABILISTIC DISTANCES AND PHA'S FOR RANDOM EARTHQUAKES**

We used the recurrence model developed in the previous section to calculate probabilistic epicentral distances for random earthquakes of \( 5.5 \leq M_L < 6.5 \) in the Wasatch Front region. The selection of this magnitude range is based on a typical threshold for major damage of \( M_L \sim 5.5 \) and the estimated maximum magnitude of \( M_L \sim 6.5 \) for random background earthquakes in this region (Arabasz and others, 1992; dePolo, 1994). The size of our magnitude interval, 1.0 unit, is at the upper end of the range of magnitude intervals for which the probabilistic distance method is usually applied.

From equation (10), our best estimate for the average recurrence interval for earthquakes of \( 5.5 \leq M_L < 6.5 \) in the Wasatch Front region is 24.4 years. If it is assumed that the average rate of occurrence of such earthquakes is the same throughout this region, then \( n(5.5, 6.5) = 1/24.4 \text{ yr/86,800} \text{ km}^2 = 4.7 \times 10^{-7} \text{ events/yr/km}^2 \). The formal uncertainty on this rate is a factor of 1.5 (see table 2). Based on the seismicity map in figure 1, the assumption of a uniform seismicity rate throughout the Wasatch Front region appears to be a reasonable one for our purposes. Although some parts of this region have had more earthquakes than others during the relatively short time period of instrumental monitoring, it is unclear to what extent these apparent spatial variations in
seismicity rates will persist into the future. Thus, we believe that our estimated rate per unit area of $5.5 \leq M_L < 6.5$ earthquakes represents an acceptable average for the region.

Table 3 shows probabilistic epicentral distances for earthquakes of $5.5 \leq M_L < 6.5$ in the Wasatch Front region calculated using equation (5) and the value of $n(5.5, 6.5)$ determined above. Results are shown for the annual probability (inverse return period) of 1/200 specified by Morgan and Hall (1993) for OBE's for Utah dams, and for three other values of annual probability commonly used in seismic hazard assessments: 1/95, 1/475, and 1/2373. Because these probabilities are small, they may be considered equivalent to annual frequencies. For a Poisson process, events with annual frequencies of 1/95, 1/475, and 1/2373 have a 90% chance of not occurring during exposure times of 10, 50, and 250 years, respectively. Table 3 shows that as the annual probability decreases from 1/95 to 1/2373, the probabilistic distance decreases from 85 km to 17 km.

Also shown in table 3 are mean peak horizontal accelerations for earthquakes at these probabilistic distances calculated with an empirical equation ("attenuation relation") derived by Boore and others (1993). We chose to use their attenuation relation for use in the examples presented here because it is one of the most up-to-date relations available in the open literature. The PHA's listed are for soil sites with near-surface shear-wave velocities typical of those found in the Salt Lake Valley (see footnote 1 to table 3 and Williams and others, 1993). Calculations are shown for two different magnitudes: the maximum $M_L$ of 6.5 and the median $M_L$ of 5.8 (computed using equation (10)) for earthquakes in our selected size range of $5.5 \leq M_L < 6.5$. The median magnitude would appear to be the most logical choice for the design earthquake magnitude, but the most conservative choice would be the maximum magnitude. As the annual probability decreases from 1/95 to 1/2373, the PHA's for the median $M_L$ increase from .04 g to .13 g while those for the maximum $M_L$ increase from .06 g to .19 g. As will be discussed shortly, all of these accelerations are relatively low in comparison to typical design accelerations for these levels of probability in the Wasatch Front region.

As a check on these ground motions, we performed a probabilistic seismic hazard analysis (PSHA) for random earthquakes of $5.5 \leq M_L < 6.5$ using the method of Cornell (1968). The primary assumptions underlying this method are the same as for the probabilistic distance method: (i) that the earthquakes occur independently at a stationary average rate and (ii) that their probabilities are spatially uniform within the random earthquake source zone. However, the method itself is quite different. In a PSHA, one assumes a ground motion value such as a peak horizontal acceleration, and then calculates the rate at which it is exceeded due to earthquakes over a range of magnitudes and distances. This procedure is repeated for a series of assumed ground motion values to determine annual exceedance rate (equivalently, annual probability of exceedance) as a function of the ground motion parameter of interest.

For a site located inside a random earthquake source zone, and sufficiently distant from its boundaries, the equation for the PSHA is:

$$
\nu(z^*) = \int_{M_1}^{M_2} \int_{r_{\text{max}}}^{r_{\text{max}}} -2\pi r \frac{dN(M)}{dM} P_z(z > z^* | M, r) dr dM
$$

In this equation, $\nu(z^*)$ is the annual rate at which ground motion parameter $z$ exceeds $z^*$, $M_1$ and $M_2$ are the magnitude limits for the calculation, $r_{\text{max}}$ is the distance limit for the calculation, and $P_z(z > z^* | M, r)$ is the probability that $z > z^*$ given an earthquake of magnitude $M$ at distance $r$. The latter is given by

$$
P_z(z > z^* | M, r) = \int_{z^*}^{\infty} p_z(z | M, r) dz
$$

where $p_z(z | M, r)$ is the probability density function for $z$ given an earthquake of magnitude $M$ at distance $r$. In our PSHA, $z$ was $\log_{10}(\text{PHA})$ and $p_z(z | M, r)$ was assumed to be a normal distribution, with a mean given by the equation of Boore and others (1993) used above and a standard deviation which we designate $\sigma_{\text{atten}}$. We performed the analysis for both $\sigma_{\text{atten}} = 0.0$ and for $\sigma_{\text{atten}} = 0.23$, the value that Boore and others (1993) found for their data set. The main purpose of the calculation with $\sigma_{\text{atten}} = 0.0$ was to provide a more meaningful comparison with the PHA's we determined with the probabilistic distance method, which did not take into account the uncertainty in the PHA estimates. A secondary purpose was to evaluate the effect on the PSHA of incorporating this uncertainty into the analysis. We used an $r_{\text{max}}$ of 100 km for our calculations, as this is the maximum range of validity of the Boore and others (1993) empirical attenuation relation.

Table 3 compares peak horizontal accelerations determined using the probabilistic seismic hazard analyses with those determined by the probabilistic distance method, as described above. The PHA's from the PSHA with $\sigma_{\text{atten}} = 0.0$ are very close (within 8%) to those calculated from the probabilistic distances using the median magnitude of 5.8. This agreement lends some validity to the ground motions estimated from the probabilistic distance method. However, comparison of the results from the PHA's with $\sigma_{\text{atten}} = 0.0$ and $\sigma_{\text{atten}} = 0.23$ shows that it is important to properly account for the uncertainties in the ground motions predicted by the attenuation relation, as is done routinely in PHA's. The effect of incorporating this uncertainty into the PSHA is negligible for an annual probability of 1/95, but increases to a factor of 1.4 at an annual probability of 1/2373 (Table 3, figure 3). Perhaps coincidentally, the PHA's from the PSHA
Table 3. Probabilistic epicentral distances and peak horizontal accelerations for random earthquakes, $5.5 \leq M_L < 6.5$

| Annual probability | Probabilistic epicentral distance, $r_0$ (km) | Median $M_L$: 5.8 | Maximum $M_L$: 6.5 | Peak horizontal acceleration (g) at $r_0$ | Peak horizontal acceleration (g) from probabilistic seismic hazard analyses
<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\sigma_{atten} = 0.0$</td>
<td>$\sigma_{atten} = 0.23$</td>
</tr>
<tr>
<td>1/95</td>
<td>85</td>
<td>.040</td>
<td>.057</td>
<td>.041</td>
<td>.037</td>
</tr>
<tr>
<td>1/200</td>
<td>58</td>
<td>.053</td>
<td>.077</td>
<td>.057</td>
<td>.068</td>
</tr>
<tr>
<td>1/475</td>
<td>38</td>
<td>.074</td>
<td>.107</td>
<td>.079</td>
<td>.107</td>
</tr>
<tr>
<td>1/2373</td>
<td>17</td>
<td>.134</td>
<td>.193</td>
<td>.143</td>
<td>.205</td>
</tr>
</tbody>
</table>

1 Computed using the predictive equation of Boore and others (1993) for the randomly oriented horizontal component and site class C (soil with an average shear-wave velocity in the upper 30 m of 180 to 360 m/s).

2 Results assuming no uncertainty in the accelerations predicted by the equation of Boore and others (1993).

3 Results assuming that the base-10 logarithms of the accelerations are normally distributed around the mean values given by the equation of Boore and others (1993), with the standard deviation, $\sigma_{atten}$, of 0.23 which they calculated for their data set.

Table 4. Peak horizontal accelerations in g’s from probabilistic seismic hazard analyses.

<table>
<thead>
<tr>
<th>Annual probability</th>
<th>Central Wasatch Front region(^1), rock (Algermissen and others, 1990)</th>
<th>Central Wasatch Front region(^1), soil (Younghs and others, 1987)</th>
<th>NW Salt Lake Valley(^2), soil (Wong and others, 1995)</th>
<th>NE Salt Lake Valley(^3), soil (this study)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/95</td>
<td></td>
<td>.06 - .08</td>
<td>.08</td>
<td>.08</td>
</tr>
<tr>
<td>1/200</td>
<td></td>
<td>2 .09 - .16</td>
<td>.14</td>
<td>.13</td>
</tr>
<tr>
<td>1/475</td>
<td>.15 - .29</td>
<td>.15 - .35</td>
<td>.24</td>
<td>.26</td>
</tr>
<tr>
<td>1/2373</td>
<td>.35 - .76</td>
<td>.40 - .70</td>
<td>.46</td>
<td>.72</td>
</tr>
</tbody>
</table>

\(^1\) As used here, “Central Wasatch Front region” refers to the region for which Youngs and others (1987) developed their probabilistic ground-shaking maps: 39° 40’ N – 42° 0’ N, 111° 25’ W – 112° 20’ W. The ranges of values listed for this region are the ranges shown on the contour maps in the indicated references, excluding a small area in the southwestern corner of the Youngs and others (1987) maps which lies outside their random earthquake source zone (see footnote 2 for an exception). The boundaries of the central Wasatch Front region are 55 to 85 km from the boundaries of the Wasatch Front region shown in figure 1.

\(^2\) As Youngs and others (1987) did not publish a probabilistic ground-shaking map for a 200-year return period, this range is derived from the hazard curves shown in figures 21 and 22 of their paper. These curves are for nine representative locations in the central Wasatch Front region.

\(^3\) The numbers in this column are for a site located near the southern shoreline of the Great Salt Lake at the northern end of the Oquirrh Mts., and were read from the hazard curve in figure 6 of Wong and others (1995).

\(^4\) See figures 1 and 3 for the site location. This calculation included the contributions from random earthquakes of 5.0 $\leq M_L < 6.5$ and from earthquakes of 6.5 $\leq M_L \leq 7.25$ on the fault-specific sources listed in table 5. The Boore and others (1993) predictive equation for site class C with $\sigma_{atten} = 0.23$ was assumed (see footnotes 1 and 3, table 3).
with $\sigma_{\text{aten}} = 0.23$ are similar to those calculated from the probabilistic distances using the maximum magnitude of 6.5, with the exception of those for the annual probability of 1/95 (table 3).

As a further check on the ground motions determined from the probabilistic distance method, Table 4 summarizes results for the Wasatch Front region from three published probabilistic seismic hazard analyses: A study by Algermissen and others (1990) for the United States, a study by Youngs and others (1987) for the central Wasatch Front region, and a study by Wong and others (1995) for a site in the northwestern corner of the Salt Lake Valley. The central Wasatch Front region studied by Youngs and others (1987) is a 75 km by 260 km area located in the middle of the region shown in figure 1 (see footnote 1, table 4), and includes the site evaluated by Wong and others (1995). The PHA's in table 4 from the studies of Youngs and others (1987) and Algermissen and others (1990) are the ranges of values they obtained for different sites in the central Wasatch Front region. These two analyses, and that of Wong and others (1995), were done using elaborate generalizations of equation (11) which take into account not only random earthquakes but also earthquakes on known faults, and cover a wide range of possible earthquake magnitudes from 5.0 or less to 7.3 or larger. All three of these studies accounted for the uncertainties in the empirical predictions of PHA's in a manner similar to that described above. To varying degrees, they also accounted for uncertainties in other aspects of the analysis.

The probabilistic PHA's found for the central Wasatch Front region in these three studies (columns 2-4, table 4) are all larger than the PHA's computed from the probabilistic distances (columns 3 and 4, table 3)—even those computed for the maximum random earthquake of $M_l 6.5$. For the PHA's computed from probabilistic distances using the median $M_l$ of 5.8, the differences range from a factor of 1.5-2.0 for an annual probability of 1/95 to a factor of 2.6-5.7 for an annual probability of 1/2373. These comparisons suggest that the probabilistic distance method might systematically underestimate the ground-shaking hazard, even for return periods of less than 200-500 yrs for which random earthquakes of $M_l < 6.5$ are the dominant source of hazard (as shown by Youngs and others, 1987; Arabasz and others, 1992; and Wong and others, 1995). However, these comparisons are not definitive because they rely on PSHA's from the literature which were done using different attenuation relations and recurrence models than those we used in applying the probabilistic distance method. In the next section, we present a more complete PSHA of our own which provides a more meaningful comparison to the results we obtained with the probabilistic distance method.

A MORE COMPLETE PROBABILISTIC SEISMIC HAZARD ANALYSIS

In this section, we present a revised and updated version of a simplified probabilistic seismic hazard analysis which we published in Arabasz and others (1992). As in that paper, the site that we use for the calculation is the intersection of Interstates 15 and 80 in the city of South Salt Lake (star, figure 1). This site is located approximately halfway between the surface traces of the Wasatch and West Valley faults.

In this analysis, the contribution of random earthquakes to the seismic hazard is computed in the same manner as described above (equations (11) and (12)), except that earthquakes down to $M_l 5.0$ are included. We use a minimum magnitude of 5.0 for our calculations, as in the PSHA's of Youngs and others (1987) and Wong and others (1995), because first, this is the minimum magnitude for which the attenuation relation of Boore and others (1993) is calibrated and second, earthquakes smaller than $M_l 5.0$ rarely cause structural damage.

In addition to the hazard from random earthquakes of $M_l 5.0$ to 6.5, our analysis includes the hazard from potential earthquakes of $6.5 \leq M_w \leq 7.25$ on known faults in the region (figure 1, table 5). We assume the maximum magnitude model for these fault-specific sources (Wesnousky and others, 1983; Wesnousky, 1986). According to this model, each fault or fault segment generates only earthquakes of maximum (sometimes referred to as "characteristic") size, together with their associated aftershocks and possible foreshocks. Some support for the applicability of this model to the Wasatch Front region comes from the observation that there has been little or no seismic activity associated with the major faults in this region since instrumental seismic monitoring began in 1962 (see figure 1 and Arabasz et al., 1992). Similar observations hold for most, if not all, of the major active faults throughout the Intermountain Seismic Belt (Smith and Arabasz, 1991). For the fault-specific sources, we compute the contribution to the annual probability of exceedance of a given peak acceleration as the product of two factors: (i) the annual probability of occurrence of the maximum earthquake and (ii) the probability that the given peak acceleration level will be exceeded if an earthquake of the specified magnitude and distance occurs (equation (12)). This procedure does not take into account the uncertainties in the magnitudes and annual probabilities of the maximum earthquakes, but such refinements are unimportant for our purposes here.

The probabilities of occurrence for the maximum earthquakes are approximated by the inverses of their average recurrence intervals. Cornell and Winterstein (1988) showed that this approximation is adequate as long as the time interval since the last maximum event on a fault does not exceed the average recurrence interval for such events. Of the faults that we considered (table 5), the only one that
does not appear to meet this criterion based on present data is the Brigham City segment of the Wasatch fault (McCalpin and Forman, 1994; table 6). This fault segment is a relatively small contributor to the probabilistic seismic hazard at the site that we are using for our calculation.

Table 5 lists basic information for five active faults in the Salt Lake Valley region that we included as potential sources of $M_w \geq 6.5$ earthquakes in our probabilistic seismic hazard analysis. Although there are many other active faults in the Wasatch Front region (see Hecker, 1993, for a recent summary), the faults listed in table 5 appear to be the primary contributors to the ground-shaking hazard in the Salt Lake Valley (Youngs and others, 1987; Wong and others, 1995). Most of the fault segment lengths and maximum magnitude estimates in table 5 are taken from table 1 of Wong and others (1995). The exceptions are those for the Nephi segment of the Wasatch fault, which was not included in their table, and the Stansbury fault, which we have subdivided into two segments based on recent work by Helm (1995). Following Wong and others (1995), we calculated maximum magnitudes for these fault segments from their lengths and estimated rupture areas using the empirical relations of Wells and Coppersmith (1994) and an assumed fault width (down-dip fault extent) of 18.3 km.

<table>
<thead>
<tr>
<th>Fault source: Identification label on figure 1</th>
<th>Straight-line length (km)</th>
<th>Maximum magnitude ($M_W$)</th>
<th>Minimum horizontal distance to site (km)</th>
<th>Average recurrence interval for maximum earthquake (yr)</th>
<th>Annual probability of maximum earthquake ($10^{-4}$/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wasatch fault segments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brigham City: BC</td>
<td>36</td>
<td>7</td>
<td>70</td>
<td>3,160</td>
<td>6.3</td>
</tr>
<tr>
<td>Weber: WB</td>
<td>56</td>
<td>7\textsuperscript{1/4}</td>
<td>14</td>
<td>3,160</td>
<td>6.3</td>
</tr>
<tr>
<td>Salt Lake City: SL</td>
<td>39</td>
<td>7</td>
<td>0</td>
<td>3,160</td>
<td>6.3</td>
</tr>
<tr>
<td>Provo: PR</td>
<td>59</td>
<td>7\textsuperscript{1/4}</td>
<td>26</td>
<td>3,160</td>
<td>6.3</td>
</tr>
<tr>
<td>Nephi: NP</td>
<td>38</td>
<td>7</td>
<td>71</td>
<td>3,160</td>
<td>6.3</td>
</tr>
<tr>
<td>West Valley fault zone: WV</td>
<td>16</td>
<td>6\textsuperscript{1/2}</td>
<td>0</td>
<td>2,000</td>
<td>5.0</td>
</tr>
<tr>
<td>East Great Salt Lake fault segments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Promontory Mountains: PM</td>
<td>50</td>
<td>7</td>
<td>70</td>
<td>4,000</td>
<td>2.5</td>
</tr>
<tr>
<td>Antelope Island: AI</td>
<td>50</td>
<td>7</td>
<td>20</td>
<td>4,000</td>
<td>2.5</td>
</tr>
<tr>
<td>Northern Oquirrh fault: NO</td>
<td>32</td>
<td>7</td>
<td>29</td>
<td>10,000</td>
<td>1.0</td>
</tr>
<tr>
<td>Stansbury fault segments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North: SN</td>
<td>17</td>
<td>6\textsuperscript{1/2}</td>
<td>64</td>
<td>10,000</td>
<td>1.0</td>
</tr>
<tr>
<td>South: SS</td>
<td>21</td>
<td>6\textsuperscript{1/2}</td>
<td>68</td>
<td>10,000</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\textsuperscript{1}Fault segment length and maximum magnitude estimates (rounded to the nearest \( \frac{1}{4} \) unit) are from Wong and others (1995) and Machette and others (1991, 1992), except those for the Stansbury fault and the Nephi segment of the Wasatch fault (see text).
\textsuperscript{2}Horizontal distance from the approximate surface projection of the fault to the site used for the calculation of the hazard curves: the intersection of I-15 and I-80 in South Salt Lake at \( 40^\circ 43.1' \) N, \( 111^\circ 54.2' \) W.
\textsuperscript{3}From Table 6.
\textsuperscript{4}Keaton and others (1993).
\textsuperscript{5}Pechmann and others (1987); Arabasz and others (1992).
\textsuperscript{6}Conservative estimate inferred from the observation that the time interval between the last two surface-faulting events was 13,300 to 22,100 \(^{10}\)C years (Olig and others, 1994), together with generic arguments by Arabasz and others (1987).
\textsuperscript{7}Conservative estimate inferred from the observation that the last surface-faulting event on at least the northern part of the fault was more than 18,000 years ago (Helm, 1995), together with generic arguments by Arabasz and others (1987).
Table 6. Calculations of average recurrence intervals for surface-faulting earthquakes during the last 6,000 years on the five central segments of the Wasatch fault

<table>
<thead>
<tr>
<th>Fault segment</th>
<th>A Age of oldest faulting event (cal yr B.P.)</th>
<th>B Age of youngest faulting event (cal yr B.P.)</th>
<th>C Time between A and B (yr)</th>
<th>E Number of faulting events</th>
<th>I Number of faulting intervals</th>
<th>Average recurrence interval on fault segment (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brigham City</td>
<td>6,000 ± 200</td>
<td>2,400 ± 100</td>
<td>3,600 ± 300</td>
<td>4</td>
<td>3</td>
<td>1,200 ± 100</td>
</tr>
<tr>
<td>Weber</td>
<td>3,750 ± 250</td>
<td>500 ± 300</td>
<td>3,250 ± 550</td>
<td>4</td>
<td>3</td>
<td>1,080 ± 180</td>
</tr>
<tr>
<td>Salt Lake City</td>
<td>5,300 ±450</td>
<td>1,300 ± 250</td>
<td>4,000 ± 700</td>
<td>4</td>
<td>3</td>
<td>4,330 ± 230</td>
</tr>
<tr>
<td>Provo</td>
<td>5,300 ±300</td>
<td>500 ± 200</td>
<td>4,800 ± 500</td>
<td>3</td>
<td>2</td>
<td>2,400 ± 250</td>
</tr>
<tr>
<td>Nephi</td>
<td>5,300 ±200</td>
<td>~400</td>
<td>4,900 ± 200</td>
<td>3</td>
<td>2</td>
<td>2,450 ± 100</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>20,550 ± 2,250</td>
<td>18</td>
<td>13</td>
<td>1,580 ± 170</td>
</tr>
</tbody>
</table>

1 Modified from table 2 of Machette and others (1992) by incorporating new data for the Brigham City and Salt Lake City segments from McCalpin and Forman (1994) and Black and others (1995), respectively.

2 All ages and time intervals (columns A-C) are rounded to the nearest 50 years, as in the original table.

3 Average recurrence intervals are determined by dividing the total time interval (column C) by the number of intervals between faulting events (column I) and rounding to the nearest 10 years. The error bars given for these numbers reflect only the uncertainties in the ages of the oldest and youngest events.

4 For the Nephi segment, the age given for the oldest faulting event is the age of a faulted datum, and is therefore a maximum age.

5 This number is a segment recurrence interval averaged over all five central segments of the Wasatch fault. Dividing this number by five gives an average composite recurrence interval—the average time between surface-faulting events anywhere on the central Wasatch fault—of 320 ± 40 years.

For the Wasatch fault, our analysis includes only the five segments in the central portion of the fault which have had repeated Holocene movement (Machette and others, 1991; 1992). The other segments of the Wasatch fault are less active and are located more than 100 km from our site. For the five central segments of the fault, we chose to calculate the annual probability for surface-faulting earthquakes from a recurrence interval averaged over all five segments (table 6, updated from Machette and others, 1992). In our judgment, this average recurrence interval is more appropriate to use than the average recurrence intervals computed for individual segments, which are based on only two or three interevent times (table 6) and hence not as reliable. The sources of the recurrence intervals for the other fault-specific sources are documented in the footnotes to table 5.

Figure 3 shows the results of our probabilistic seismic hazard analysis in the form of a graph of annual exceedance rate versus peak horizontal acceleration (solid line). Also shown are results for separate analyses with the fault-specific sources only, random earthquakes of 5.0 ≤ M<sub>L</sub> < 6.5 only, and random earthquakes of 5.5 ≤ M<sub>L</sub> < 6.5 only. All of these calculations were done using the Boore and others (1993) attenuation relation with σ<sub>atten</sub> = 0.23, except for one set of calculations done for 5.5 ≤ M<sub>L</sub> < 6.5 random earthquakes using σ<sub>atten</sub> = 0.0 (discussed previously and labeled on figure 3). The graphs in figure 3 show that at least at this site in the Wasatch Front region, the ground-shaking hazard is significantly underestimated if only the contribution from random earthquakes of 5.5 ≤ M<sub>L</sub> < 6.5 is considered. This holds true even at return periods shorter than 300 years, where figure 3 shows such earthquakes to be the dominant contributors to the ground-shaking hazard. Note that at these short return periods, one cannot neglect the contributions to annual probabilities of ground motion exceedance from earthquakes of either M<sub>L</sub> < 5.5 or of M<sub>L</sub> > 6.5.

The last column of table 4 lists the peak horizontal accelerations that we determined from our PSHA for the four annual probabilities (exceedance rates) that we have focused on in this paper. Note that these PHA's are quite comparable to those in the preceding three columns, which are from other PSHA's for the central Wasatch Front region. The accelerations we determined from our PSHA are significantly larger than those we determined from the probabilistic distance method (table 3) for either the median M<sub>L</sub> case or the maximum M<sub>L</sub> case. Using the former as the basis for comparison, the difference is a factor of 2.0, 2.5, 3.5, and 5.4 for annual probabilities of 1/95, 1/200, 1/475, and 1/2373, respectively. Thus, there appears to be a serious problem with using the probabilistic distance method to
Figure 3. Annual exceedance rate for peak horizontal ground accelerations on soil at the intersection of I-15 and I-80 in South Salt Lake at approximately 40°43′1″N, 111°54′2″W (star, figure 1). Results are shown for calculations variously using random earthquakes of $5.5 \leq M_r < 6.5$, random earthquakes of $5.0 \leq M_r < 6.5$, the fault-specific sources listed in table 5, and the latter two combined. All of these calculations were done using the predictive equation of Boore and others (1993) for the randomly-oriented horizontal component and site class C (soil with an average shear-wave velocity in the upper 30 m of 180 to 360 m/s). $\sigma_{\text{atten}}$ is the standard deviation of the base-10 logarithms of the accelerations predicted by their equation. $\sigma_{\text{atten}}$ was set equal to 0.23, the value found by Boore and others (1993), for all calculations except for the curve labeled $\sigma_{\text{atten}} = 0$ (see text and equations (11) and (12). The horizontal lines mark selected values of average return period (inverse of annual exceedance rate) used in this paper.

determine design ground motions for a specified annual probability of exceedance, at least at this particular site in the Wasatch Front region and in the way that we have done it here.

DISCUSSION

The simple calculations that we have presented in this paper show that in the Wasatch Front region, use of the probabilistic distance method to determine design earthquakes and corresponding ground motions will generally under-estimate the ground-shaking hazard. To put it another way, the mean ground motion parameters estimated for the design (random) earthquake will, in general, occur more frequently than the design earthquake itself. There are two reasons for this. The first and foremost reason is that the probabilistic distance method only takes into account the hazard from random earthquakes. In the Wasatch Front region, however, potential larger earthquakes of up to $M_w \approx 7.5 \pm 0.25$ on known faults are also significant contributors to the hazard, even at relatively short return periods. A related problem with the probabilistic distance method is that it is typically applied only to random earthquakes in a fairly narrow magnitude interval such as 0.5 to 1.0 unit, whereas random earthquakes ranging from $M_r = 5.0$ to at least 6.5 constitute a significant source of seismic hazard in the Wasatch Front region. As a comparably wide range of earthquake magnitudes also contributes to the
ground-shaking hazard in many other seismically active regions, we believe that our conclusion regarding the probabilistic distance method is likely to apply to other regions as well.

The second reason why use of the probabilistic distance method can result in underestimation of the ground-shaking hazard is that this method does not directly incorporate the effects of uncertainty in the empirical predictions of ground motion. This limitation is not inherent to the method, however, as the effects of such uncertainty could easily be factored into the calculations of ground motions for a particular probabilistic distance and magnitude. Note that although we have based all of our conclusions regarding the probabilistic distance method on sample calculations using PHA's, we expect that the same conclusions hold for other ground motion parameters as well.

We do not know to what extent, if any, use of the probabilistic distance method may have resulted in inadequate criteria for the design or evaluation of dams or other facilities in Utah or elsewhere. The OBE—as we infer from Utah's statutes for dam safety (Morgan and Hall, 1993)—should be only part of what is considered in selecting ground motion parameters for evaluating the performance of a planned or existing dam. We wish to emphasize, however, that the probabilistic distance method was used in a sound and appropriate manner in the USBR report by Sullivan and others (1988) from which we took Wood and Ostenaa's (1984) description of it. Sullivan and others (1988) calculated probabilistic epicentral distances corresponding to small annual probabilities of 1/50,000 to 1/100,000 for magnitude 6-plus earthquakes in the Wasatch Front region. From their resulting epicentral distances of 2.4 to 5.1 km, they argued that at these probability levels, which are conservative standards used for the design of critical structures such as dams, a magnitude 6 to 6.5 random earthquake could occur in the near vicinity of any site in the Wasatch Mts. Based in part on their analysis, the recently completed Jordanelle Dam in the Wasatch Mts. was designed to withstand a magnitude 6.5 near-field earthquake as well as ground motions exceeding those expected for a magnitude 7.5 earthquake on the Wasatch fault ~30 km away (Wilson, 1988).

Our work, as well as that of Youngs and others (1987) and Wong and others (1995), has shown that at return periods of up to a few hundred years, potential earthquakes with a wide variety of magnitudes and distances contribute significantly to the ground-shaking hazard at most sites in the Wasatch Front region. The only technique we know of that can successfully account for the contributions of all of these sources to the hazard is probabilistic seismic hazard assessment (Cornell, 1968). For this reason, this technique provides a more conservative means for determining design ground motions for short return periods than does the probabilistic distance method. Although in this paper we have applied PSHA only to determine peak horizontal accelerations, this technique is quite general and can be used to compute probabilities of exceedance for any ground motion parameter for which a suitable predictive equation exists. Empirical predictive equations have been developed not only for peak horizontal accelerations but also for peak horizontal velocities and displacements and for various types of response spectral values (see Joyner and Boore, 1988, for a review). Because response spectra are particularly useful for many engineering applications, PSHA is often used to compute "equal hazard" response spectra. For situations where a site-specific PSHA to determine a response spectrum is not practical, Youngs and others (1987) present some equal hazard response spectral shapes for the Wasatch Front region and describe a procedure for scaling such spectra for specific sites using their maps of probabilistic peak horizontal acceleration.

In cases where a specific design earthquake for a relatively short return period is needed, such as an OBE for a Utah dam, we suggest the following procedure as an alternative to the probabilistic distance method. First, the results of a site-specific or regional PSHA should be used to determine an appropriate design value for the return period of interest for the ground motion parameter most critical to the design of the structure. Then, a design earthquake can be selected which will generate ground motions with the desired characteristic at the site. For example, for an OBE for a Utah dam, one might select as the design earthquake a random earthquake of the maximum magnitude of $M_0 = 6.5$. This choice is usually the most conservative one for a random earthquake because the duration of ground shaking increases with magnitude. Alternatively, one might select an earthquake from the magnitude increment which contributes the most to the probability of exceedance at the return period for which the deterministic seismic hazard assessment is being performed. In a state-of-the-art PSHA, the process of "de-aggregation" yields the mean magnitude and distance of such a controlling earthquake. Once the magnitude of the design earthquake has been decided upon, the predictive equation for the critical ground motion parameter can be used to select the distance for the design earthquake which will produce the appropriate value of the parameter at the site. Wong and others (1995) recently used this procedure to select an OBE for a mine tailings impoundment in the northwestern Salt Lake Valley. In situations where there is more than one critical ground motion parameter, then this procedure can be repeated as necessary to select additional design earthquakes.

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