Appendix B
Developing Standard Response Spectra and Effective Peak Ground Accelerations for Use in the Design and Evaluation of Civil Works Projects

B-1. Introduction

a. Purpose. The purpose of this appendix is to provide a procedure for developing standard acceleration response spectra and effective peak ground accelerations for use in the seismic design and evaluation of structural features of USACE projects as required by ER 1110-2-1806. The standard response spectra can be used as a starting point for performing seismic designs and evaluations, and, if needed, for determining dynamic analysis requirements for more refined analysis. A specific goal of this appendix is to update previous guidance documents to include the information available in the 2000 National Earthquake Hazards Reduction Program (NEHRP) Recommended Provisions for New Buildings and Other Structures (FEMA 368), which are based on the most recent representation of the national ground shaking hazard.

b. Scope. Guidance is provided for using the most recent national seismic hazard data for determining both horizontal and vertical acceleration response spectra. Guidance is also provided for determining effective peak ground accelerations and seismic coefficients for use in seismic stability analyses.

c. Background. Previous guidance memoranda were prepared before the 2000 NEHRP Recommended Provisions were published. The recommended procedures in those documents were initially based on the spectral maps contained in the 1991 NEHRP provisions, and later on the maps contained in the 1994 NEHRP provisions. Over the years, there have been significant changes in the seismic hazards maps and their application to estimate ground shaking hazard levels. The 1997 NEHRP provisions introduced a more detailed procedure for estimating site specific design response spectra. The procedure in the current provisions is based on probabilistic estimates associated with a 2% probability of occurrence in 50 years bounded in some areas by deterministic thresholds, provide spectral ordinates at periods of 0.2 and 1.0 seconds. In addition, probabilistic seismic hazard information is currently available in the form of maps for peak ground acceleration and spectral ordinates at periods of 0.2 and 1.0 seconds which are available for probabilities of exceedance of 10% in 50 years and 2% in 50 years. Note that only the USGS probabilistic seismic hazard maps may be used in seismic design and evaluation of hydraulic structures, and not the MCDE maps. The MCDE maps are used in seismic design and evaluation of building structures and are mentioned here to provide background on NEHRP provisions.

d. Definitions

(1) Peak ground acceleration. The peak ground acceleration (PGA) is the maximum amplitude of the ground acceleration time history. In terms of structural response, it represents the peak value of the absolute acceleration of a single degree of freedom (SDOF) system with infinite stiffness, that is, with a natural period of vibration equal to zero.

(2) Effective peak ground acceleration and effective peak ground velocity.

(a) Several definitions and different physical interpretations have been proposed for this parameter with the purpose of quantifying the severity of design ground shaking. The concepts of effective peak acceleration (EPGA) and effective peak velocity (EPGV) have been employed to define design ground motions for use in model building codes. They were introduced in the Applied Technology Council (ATC-3 1978) seismic provisions as convenient normalizing factors for construction of design response spectra for ground motions of normal duration. The EPGA is proportional to spectral ordinates for periods in the range of 0.1 to 0.5 seconds, while the EPGV is proportional to spectral ordinates at a period of about 1 second. The constant of proportionality (for a 5 percent damping spectrum) was set at a standard value of 2.5 in both cases. The EPGA and EPGV are related to peak ground acceleration and peak ground velocity but are not necessarily the same as or directly proportional to peak acceleration and velocity. When very high frequencies are present in the ground motion, the EPGA may be significantly less than the peak ground acceleration. In general, if one examines the ratio between the spectral ordinate at period 0.2 seconds and the corresponding PGA value at individual locations in the national probabilistic hazard maps, the value of the ratio is variable and generally less than 2.5.

(b) Newmark and Hall (1982) characterized the effective peak acceleration as the acceleration value that is most closely related to structural response and to damage potential of an earthquake. That is, this concept of effective peak acceleration is intended to reflect the actual damage potential of the seismic excitation, which cannot be completely described only by the peak value of the ground acceleration. The definition of the effective peak acceleration therefore must take into account not only the amplitude of the excitation, but also of its frequency content and the type and characteristics of the general structural system under consideration.

(3) Response spectra.

(a) A response spectrum is a plot of the peak values of the response (displacement, velocity, or acceleration) of a number of SDOF systems with different natural vibration periods subjected to the same seismic input. Therefore, an acceleration response spectrum represents the peak accelerations that a suite of SDOF systems with a range of natural periods may exhibit for a given component of ground motion.

(b) In general, the acceleration response spectrum associated with a specific time history recorded at a given location has a jagged shape with significant peaks and valleys. The response spectrum for another ground motion recorded at the same site during a different earthquake will exhibit also an irregular shape, but the peaks and valleys will not necessarily coincide with those in the previous one.

(c) Therefore, appropriately smoothed spectra are usually defined for design and evaluation purposes. These spectra are termed design response spectra. They do not represent the acceleration response from a single ground motion time history, but rather they are intended to be representative of all the ground motions that can be expected at a given site. There are two basic approaches for the development of design response spectra: site-specific procedure or standard procedure.

(d) Site-specific response spectra. Site-specific response spectra are developed using source to site distances, appropriate attenuation relationships, expected magnitudes and actual local site conditions. Therefore, it is typically assumed that site specific studies will provide more accurate acceleration spectra than using the codified standard acceleration spectra. EM 1110-2-6050 describes the conditions requiring a site specific ground motion study. Site-specific response spectra can be generated by means of a deterministic seismic hazard analysis (DSHA) or a probabilistic seismic hazard analysis (PSHA). In the DSHA, the site ground motions are estimated for a specific earthquake, defined as a seismic event of a certain magnitude for a particular seismic source occurring at a certain distance from the site. The representation of the ground motions in terms of the corresponding site-specific response spectra is achieved by using appropriate attenuation relationships. Information on this approach can be found in EM 1110-2-6050. The PSHA is an approach that uses the likelihood (probability) that a given level of ground motion will occur during a specific exposure period. In the PSHA, the site ground motions are defined for selected values of the probability of exceedance in a given time exposure period, or for selected values of annual frequency or return period for ground motion exceedance. This approach incorporates the frequency of occurrence of earthquakes of different magnitudes on the seismic sources, the uncertainty of the earthquake locations on the sources, and the ground motion attenuation including its uncertainty. The response spectra developed by a PSHA represent equal or uniform hazard spectra, in which each spectral ordinate has an equal probability of exceedance. EM 1110-2-6050 describes the procedures for probabilistically estimating earthquake ground motions.

(e) Standard response spectra. Standard response spectra are based on a general characteristic shape that is defined in terms of estimates of selected ground motion parameters, which can be effective peak ground accelerations or spectral accelerations. EM 1110-2-6050 describes the approach proposed by Newmark and Hall (1982) to develop design response spectra using peak ground motion parameters (peak ground acceleration, velocity and displacement), multiplied by a series of appropriate spectral amplification factors that depend on the damping level.

(4) Probability of exceedance. The probability of exceedance represents the chance, expressed as a percentage (%), that a more severe ground motion will occur within a specified exposure time expressed in number of years. Assuming that the temporal occurrence of the earthquake follows a Poisson process, the probability of exceedance (P_e) in a given exposure time (T_e) is related to the annual probability of exceedance (λ_m) as follows:

$$P_e = 1 - e^{-\lambda_m T_e} \tag{1}$$

The reciprocal of the annual probability of exceedance is the return period ($T_R = 1/\lambda_m$), which represents the average number of years between exceedances. For a given (P_e, T_e) pair, the corresponding return period can be obtained as follows:

$$T_R = -\frac{T_e}{\ln(1 - P_e)} \tag{2}$$

As an example, an earthquake having a probability of exceedance of 2% in 50 years would have a mean return period of 2,475 years, whereas an earthquake having a probability of exceedance of 10% in 50 years would have a mean return period of 475 years. The following table summarizes the return periods for some of the most common combinations of probabilities of exceedance and exposure time:

Table B-1. Approximate return periods for different probabilities of exceedance and exposure times

Prob. of Exceedance	**Exposure Time** [years]	**Return Period** [years]
50%	100	144
10%	50	475
10%	100	950
5%	100	1,950
2%	50	2,475
1%	100	9,950

(5) Operating basis earthquake (OBE). The OBE is an earthquake that can reasonably be expected to occur within the service life of the project, that is, with a 50 percent probability of exceedance during the service life. (This corresponds to a return period of 144 years for a project with a service life of 100 years.) The associated performance requirement is that the project will show little or no damage without interruption of function. The purpose of the OBE is to protect against economic losses from damage or loss of service. Therefore alternative choices of return period for the OBE may be based on economic considerations. In a site-specific study the OBE is determined by a PSHA (ER 1110-2-1806).

(6) Maximum design earthquake (MDE). The MDE is the maximum level of ground motion for which a structure is designed or evaluated. The associated performance requirement is that the project performs without catastrophic failure, such as uncontrolled release of a reservoir, although severe damage or economic loss may be tolerated. The MDE can be characterized as a deterministic or probabilistic event (ER 1110-2-1806).

(7) Maximum credible earthquake (MCE). The maximum <u>credible</u> earthquake represents the earthquake hazard level used for design and evaluation of critical features of high hazard projects as defined by ER 1110-2-1806. The Maximum Credible Earthquake is defined as the greatest earthquake that can reasonably be expected to be generated by a specific source on the basis of the available seismological and geological evidence. The Maximum Credible Earthquake is determined by a deterministic seismic hazard analysis. Since buildings are not classified as critical facilities, the use of a Maximum Credible Earthquake as defined in ER 1110-2-1806 is not required for the building structures.

(8) Seismic coefficient method. In the seismic coefficient method, the inertial force is assumed to act in a horizontal direction at the center of mass of the structure, based on the assumption that the structure is a rigid body. However, the use of the rigid body concept often underestimates the magnitude of the actual inertial actions because of the amplification effects associated with the flexibility of the structure.

(9) Dynamic analysis procedures. Linear dynamic analysis procedures are presently used for earthquake-resistant design and safety evaluation of hydraulic structures. Linear dynamic analysis is typically based on modal decomposition techniques, in which the total response of a structure is obtained by combining the response of its individual modes of vibration, calculated separately. Linear dynamic analysis is adequate for structures whose seismic response stays within the linear elastic range and it can be performed using response spectrum analysis or time-history analysis.

(a) Response spectrum analysis. In the response spectrum analysis, the peak response of the structure is evaluated by combining estimates of the maximum responses from individual modes and multicomponent input. The seismic input is defined in terms of ground response spectra.

(b) Time history analysis. This type of analysis involves the computation of the complete response history of the structure to the earthquake, and not just the peak values. The seismic input is given by actual or simulated acceleration time histories.

B-2. Seismic hazard and design maps

a. USGS probabilistic maps. The U.S. Geological Survey (USGS) National Hazard Mapping Project supported by NEHRP provides the latest peer reviewed and published seismic hazard data for the US. This data is provided in probabilistic hazard maps and interactive web based query for certain ground motion parameters. The current link to this project site is located at the following address: http://eqhazmaps.usgs.gov/. However, this could change and it may be necessary to search for the most current web link. The available probabilistic maps for downloading or viewing correspond to PGA values and 0.2 sec and 1.0 sec spectral acceleration values for probabilities of exceedance of 10% in 50 years (return period of 475 years) and 2% in 50 years (return period of 2,475 years). The site also provides an interactive menu where the user can obtain the above mapped values for a given location specified by latitude / longitude. Ground motion values for the 48 states have been calculated for a grid spacing of 0.05 degrees. Interpolated values are typically calculated using the four surrounding corner points. For guidance, 0.1 degree latitude is about 6.8 miles, and 0.1 degree longitude varies but for the 48 states is on the order of 5.6 miles. Figures B-1 and B-2 show the probabilistic maps for the 0.2 and 1-second spectral acceleration values corresponding to a probability of exceedance of 2% in 50 years.

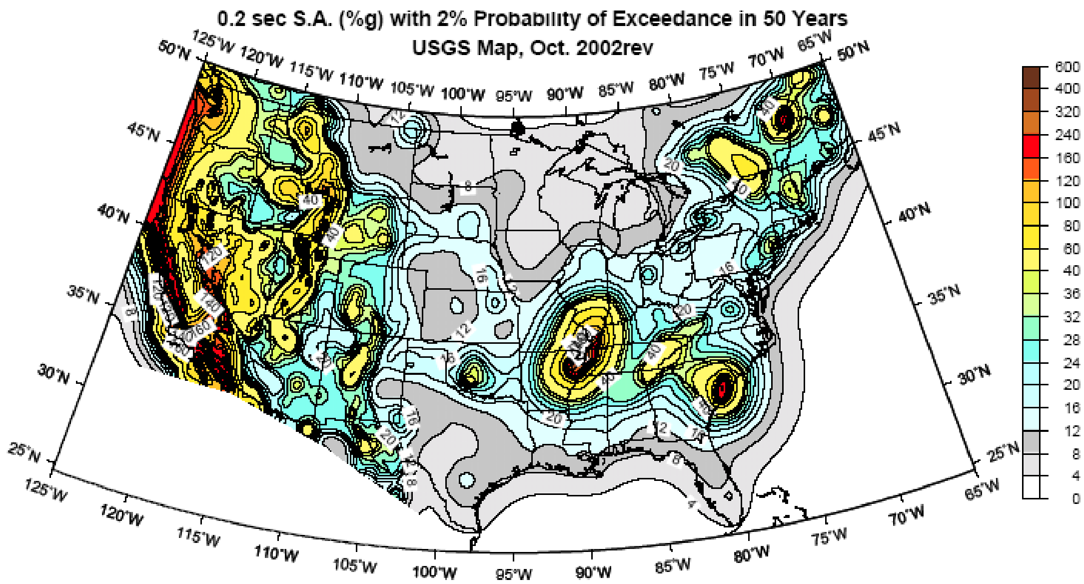

Figure B-1. 0.2-second spectral acceleration with 2% probability of exceedance in 50 years

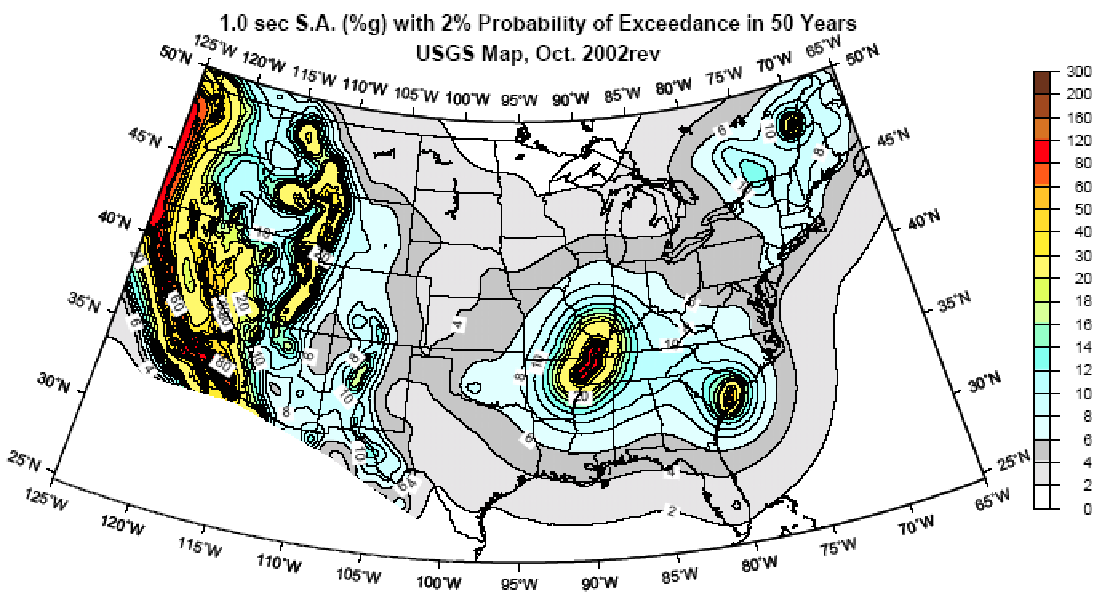

Figure B-2. 1-second spectral acceleration with 2% probability of exceedance in 50 years

b. MCE design maps. Most recent NEHRP provisions define seismic hazards in terms of "Maximum Considered Earthquake" ground motions, which are based on a set of rules that depend on the seismicity of a region. The design ground shaking level for new building structures is defined as 1/1.5 = 2/3 of the maximum considered earthquake ground motion. For most regions of the nation, the maximum considered earthquake ground motion is defined with a uniform probability of exceedance of 2% in 50 years (return period of about 2,500 years). For regions of high seismicity (such as coastal California) the seismic hazard is typically controlled by large-magnitude events occurring on a limited number of well-defined fault systems. The ground shaking calculated at a

2% PE / 50 years would be much larger than that which would be expected based on the characteristic magnitudes of earthquakes on these known active faults. For regions of high seismicity, it is more appropriate to directly determine the maximum considered earthquake motions based on the actual characteristics of these faults. The ground shaking in these cases is defined based on the median estimate of the ground motion resulting when the characteristic earthquake is multiplied by 1.5 to achieve the appropriate level of conservatism.

B-3. Development of standard horizontal response spectrum

a. Seismic hazard data. The following recommended procedure for developing standard spectra for use in the preliminary design and analysis of USACE civil works structures is based on the current probabilistic seismic hazard data. For a given site location, the spectral ordinates at periods of 0.2 and 1.0 seconds are available for probabilities of exceedance of 10% in 50 years and 2% in 50 years. These ground motion values are calculated for firm rock sites. The spectral ordinate at periods 0.2 and 1 seconds are denoted as S_S and S_1.

b. Site effects.

(1) The shape of the standard response spectra can be modified to reflect site characteristics. The effects of the soil and foundation conditions can greatly affect the structural response. These site effects are accounted for in the development of the standard response spectra by the use of site coefficients that scale the spectral ordinates to the appropriate values for other local conditions such as those defined in Table B-2.

(2) Site class F is omitted from the table because this site classification requires site-specific investigations and a standard response spectrum should not be employed for this case. The site coefficients F_a and F_v are given in Tables B-3 and B-4. These two coefficients F_a and F_v scale the values of S_S and S_1, respectively, which were determined for firm rock conditions (characterized by a shear-wave velocity of about 2,500 ft/sec in the top 100 ft).

(3) The independent scaling of the spectral parameters using these factors modifies not only the spectral amplitudes but also the shape of the spectrum by changing the maximum amplification plateau. The scaled maximum considered earthquake spectral values are designated as $\overline{S}_S$ and $\overline{S}_1$, for short and 1-second period responses. They are given by the following expressions:

$$\begin{aligned} \overline{S}_S &= F_a S_a \\ \overline{S}_1 &= F_v S_1 \end{aligned} \qquad (3)$$

Table B-2. Site classification

Site Class	Description
A	Hard rock with $\bar{v}_s > 5{,}000\,\text{ft/sec}$
B	Rock with $2{,}500\,\text{ft/sec} < \bar{v}_s \leq 5{,}000\,\text{ft/sec}$
C	Very dense soil and soft rock with $1{,}200\,\text{ft/sec} < \bar{v}_s \leq 2{,}500\,\text{ft/sec}$ or with either $\bar{N} > 50$ or $\bar{s}_u > 2{,}000\,\text{psf}$
D	Stiff soil with $600\,\text{ft/sec} \leq \bar{v}_s \leq 1{,}200\,\text{ft/sec}$ or with either $15 \leq \bar{N} \leq 50$ or $1{,}000\,\text{psf} \leq \bar{s}_u \leq 2{,}000\,\text{psf}$
E	A soil profile with $\bar{v}_s < 600\,\text{ft/sec}$ or with either $\bar{N} < 15$ or $\bar{s}_u < 1{,}000\,\text{psf}$, or any profile with more than 10 ft of soft clay

Table B-3. Site correction coefficient F_a

Site Class	Coefficient F_a				
	$S_S \leq 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9

Table B-4. Site correction coefficient F_v

Site Class	Coefficient F_v				
	$S_1 \leq 0.10$	$S_1 = 0.20$	$S_1 = 0.30$	$S_1 = 0.40$	$S_1 \geq 0.50$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4

c. Damping. The seismic hazard information is based on an inherent structural damping of 5%. If spectral values for other damping ratios are required, then the standard spectral accelerations have to be adjusted using the correction coefficients B_S and B_1 provided in Table B-5.

d. Construction of standard horizontal spectrum.

(1) To determine the standard horizontal response spectrum it is necessary to compute first the values of the two periods defining the interval of maximum spectral amplification. They are denoted as T_0 (start of maximum amplification plateau) and T_S (end of maximum amplification plateau), and they are defined as follows:

$$T_S = \frac{B_S \overline{S}_1}{B_1 \overline{S}_S}$$
$$T_0 = \frac{1}{5} T_S \qquad (4)$$

(2) The standard horizontal spectrum is then defined as follows:

$$S_A(T) = \begin{cases} \overline{S}_S\left(\left(\frac{5}{B_S} - 2\right)\frac{T}{T_S} + 0.4\right) & \text{for } 0 \le T < T_0 \\ \frac{\overline{S}_S}{B_S} & \text{for } T_0 \le T < T_S \\ \frac{\overline{S}_1}{B_1 T} & \text{for } T_S \le T \end{cases} \qquad (5)$$

Table B-5. Damping correction coefficients B_S and B_1

Damping [%]	Coefficient B_S	Coefficient B_1
≤ 2	0.80	0.80
3	0.87	0.87
4	0.93	0.93
5	1.00	1.00
6	1.06	1.04
7	1.12	1.08
8	1.18	1.12
9	1.24	1.16
10	1.30	1.20
20	1.80	1.50

e. Spectrum construction for different probability levels

(1) The two values of spectral ordinates at periods of 0.2 and 1.0 seconds (S_S and S_1) are available for probabilities of exceedance of 10% in 50 years and 2% in 50 years, which correspond to average return periods of 475 and 2,475 years, respectively. If a standard spectrum associated with a different probability of exceedance or return period is required, then it is necessary to appropriately modify those values.

(2) It is assumed that the hazard curves relating the spectral acceleration (S_A) with the return period (T_R) can be approximated by power curve functions of the following form:

$$S_A = b(T_R)^m \tag{6}$$

This assumption implies that spectral values and return periods are linearly related in a log-log representation, that is:

$$\log(S_A) = \log(b) + m\log(T_R) \tag{7}$$

The coefficient m represents the slope of the straight line and $\log(b)$ is the intercept on the ordinate axis.

(3) Considering the available data points, which are represented by ($S_A^{T_R=475}$) and ($S_A^{T_R=2475}$), then it is possible to obtain spectral accelerations at different return periods by linear log-log interpolation. The curve coefficients are given by

$$\begin{aligned} m &= \frac{\log(S_A^{T_R=2475}) - \log(S_A^{T_R=475})}{0.7169} \\ \log(b) &= 4.7338\log(S_A^{T_R=475}) - 3.7338\log(S_A^{T_R=2475}) \end{aligned} \tag{8}$$

Using this approach, two approximated hazard curves can be defined for the spectral accelerations at periods of 0.2 and 1.0 seconds (S_S and S_1), which can be then used to determine the corresponding spectral values for other return periods different from 475 and 2,475 years.

B-4. Development of standard vertical response spectrum

a. Vertical-to-horizontal response spectral ratio. Vertical response spectra may be necessary for design and analysis of certain structures. The commonly adopted vertical-to-horizontal response spectral ratio of 2/3 (Newmark and Hall 1978) may be significantly exceeded at short periods for near-source distance conditions. Therefore, the vertical standard response spectrum should be obtained considering the source to site distance (R) by means of the factors given in Table B-6. These factors were based on the information provided in EM 1110-2-6050. In most cases of preliminary design the source-to-site distance will be unknown, and for those cases $R = 25\,\text{km}\,(15\,\text{miles})$ may be assumed. This general procedure can be applied to both standard and site-specific spectra, although in this last case vertical response spectra can also be derived directly by some attenuation relationships.

Table B-6. Conversion factor F_V for vertical response spectrum

Source to Site Distance (R)	Conversion Factor
≤ 10 km	1.00
25 km	0.84
≥ 40 km	0.67

b. Construction of standard vertical spectrum.

(1) To determine the standard spectrum it is necessary to compute first the period defining the upper limit of the maximum vertical amplification plateau, given by

$$T_{SV} = \frac{0.67}{F_V} T_S \qquad (9)$$

(2) The standard vertical spectrum is then defined as follows:

$$S_{AV}(T) = \begin{cases} F_V \, S_A(T) & \text{for } T < T_{SV} \\ 0.67 \dfrac{\overline{S}_1}{B_1 T} & \text{for } T_{SV} \le T \end{cases} \qquad (10)$$

B-5. Multi-component earthquake input

a. Second orthogonal component of horizontal ground motion. The NEHRP hazard maps are based on attenuation relationships for the random horizontal component of the ground motion, not the stronger component. If a second orthogonal component of horizontal motion is required for preliminary seismic analysis, then it should be set equal to the first orthogonal component determined as indicated in the previous section.

b. Combining multi-component earthquake input. For most structures, preliminary seismic analysis can be conducted considering a single horizontal component of earthquake ground motion. However, for those cases where the effects due to two or three components of ground motion must be taken into account, the maximum structural responses should be obtained by combining the effects of the components in accordance with the procedures described in EM 1110-2-6050.

B-6. Seismic stability analysis

a. Determination of effective peak ground acceleration (EPGA). For a given return period, the effective peak ground acceleration (EPGA) is determined by dividing by 2.5 the corresponding 5%-damping short period spectral acceleration value as follows:

$$EPGA(T_R) = \frac{\overline{S}_S^{T_R}}{2.5} \qquad (12)$$

b. Seismic coefficient. The seismic coefficient used for the preliminary seismic stability evaluation of concrete hydraulic structures should be equal to 2/3 of the EPGA value corresponding to the OBE or the MDE, expressed as a decimal fraction of the acceleration of gravity.

B-7. DEQAS-R computer program

a. Description. Due to the availability of the national probabilistic seismic hazard data, it is now possible to provide tools to assist in developing design spectra without the need to manually extract data from maps or to explicitly query the USGS web site. A set of integrated software tools has been developed to provide the needed seismic hazard data based on the most recent national probabilistic seismic hazard information. For user-specified location and return period, the current version of this program can calculate and display the horizontal and vertical standard spectra based on the procedure provided in this document. In addition, the program can generate the equal hazard spectrum for the location and return period indicated as well as the corresponding seismic hazard curves for periods of 0.2 and 1.0 seconds. The program also includes additional options to display different maps containing the most recent seismic hazard data and it provides access to relevant USACE reference documents.

b. Availability. The program DEQAS-R can be downloaded from the following website: http://chl.erdc.usace.army.mil/.

B-8. Examples

Typical example problems illustrating step-by-step implementation of the procedures in this guidance document are provided in Appendix C. The first example describes the development of a 5%-damping horizontal standard spectrum for an OBE. The second example describes the development of both horizontal and vertical standard spectra for an MDE and for a 6% damping level. The last example describes the determination of EPGA values for a specified set of return periods. The solution of each one of these examples using the computer program DEQAS-R is illustrated in Section II of Appendix C.