EARTHQUAKE MAGNITUDE AND PEAK ACCELERATION RANGES FOR SEISMIC DESIGN CONSIDERATIONS AT POINT LEPREAU, NEW BRUNSWICK.

by

P.W. Basham & D.H. Weichert

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There is a rapidly increasing need for careful assessment of earthquake hazards at sites proposed for Canadian nuclear power plants. At the same time, there is a growing recognition that traditional methods for predicting seismic ground motions at a site are not adequate at the low risk levels desired in earthquake-resistant design of nuclear power plants. These concerns have led to the formation of a Canadian Nuclear Association Subcommittee that has been charged with drafting a Canadian Standards Association code, CSA Standard N289, "Seismic Design Requirements for CANDU Nuclear Power Plants". The subcommittee is composed of representatives of AECL, AECB, Ontario Hydro, NRC and EMR.

The primary task of the EMR (Division of Seismology and Geothermal Studies, Earth Physics Branch) Subcommittee representatives is the drafting of those sections of code that describe the seismological investigations to be undertaken and the manner in which the site seismic ground motions will be defined for purposes of earthquake-resistant design of plant structures and components. EMR has also agreed to produce (within about 18 months) a regionalized map of Canada that will contain the basic earthquake occurrence information required to specify seismic ground motions with associated probabilities of exceedence for any proposed nuclear power plant site in the country. As the background work for these tasks was commencing, the question of the earthquake hazard at the proposed nuclear power plant site at Point Lepreau, New Brunswick, came to the fore with requests from a variety of agencies to EMR for guidance on estimating expected seismic ground motions at that site. In addition to providing a variety of information to the different agencies on a bilateral basis, the Division decided to assemble as rapidly as possible the seismological information relevant to the Point Lepreau site and use it as a preliminary test of concepts that were beginning to be developed for CSA Standard N289.

The results of this exercise have been presented verbally at a meeting with representatives of AECL, Canatom and New Brunswick Power Commission and a brief account follows here. The results, although they represent our best estimates available at the present time, should be considered preliminary: (i) because some of the seismological relationships employed require further testing; (ii) because the final procedures to be employed for the regionalized earthquake occurrence map will not be finalized until other seismic regions have been assessed.

The procedure that has been followed can be described in four steps:

a) choose a region surrounding the site which, on seismological and geological evidence, appears to have experienced a uniform occurence of earthquake activity.

b) estimate for the region an earthquake recurrence relationship giving occurences per unit time and per unit area as a function of magnitude and assume that earthquakes in future will occur uniformly over the region at a rate given by the recurrence relationship;

c) employ the earthquake recurrence rate, extrapolating beyond the range of observed data where necessary, to estimate the probabilities that certain magnitude earthquakes will occur at certain distances from a site within the region. (The uncertainty of such extrapolation is well-recognized and will be discussed in a later report, using non-parametric statistics.)

d) employ the earthquake recurrence relationship and a peak acceleration attenuation law to estimate the probabilities that a site within the region will experience certain peak acceleration within certain time periods.

Northern Appalachian Earthquake Zone. For this preliminary evaluation of the earthquake occurrence in the southern Maritimes, the "northern Appalachian earthquake zone" is defined as a rectangular area encompassing New Brunswick, Maine and southern Nova Scotia. The zone is bounded on the northwest about 75 km southeast of the St. Lawrence valley, thereby avoiding the higher seismicity of the lower St. Lawrence; it is bounded on the southwest by a line approximately joining Portland, Maine, and Granby, Quebec, thereby avoiding the apparently higher seismicity in the Boston area; it is arbitrarily bounded on the northeast by a line approximately joining central Gaspé and north-central Nova Scotia (in future work, the seismicity of the northern Appalachian zone will likely be assumed to extend northeast through the Gulf of St. Lawrence and into Newfoundland, until a more reliable estimate of the seismicity of the latter two areas becomes available); the zone is bounded in the Atlantic by a line from off-shore Nova Scotia to a point about 100 km east of Cape Cod. The total area of this rectangular zone is about 3.4×10^5 km^2.

Although in the following analysis it is assumed that historical earthquakes have occurred, and future earthquakes will occur, uniformly and at random throughout the zone, the epicentres of the historical earthquakes available from 1764 to 1974 indicate that the zone area may be exaggerated on its northwest and southeast edges, i.e., that the New England-Quebec border area and the Atlantic-southern Nova Scotia area may be less seismic than the central belt through Maine and New Brunswick. The influence of a possible exaggeration of area on the later results will be shown by assuming that the observed seismicity is associated with a zone of half the total area.

Magnitude-Recurrence Relation. The primary requirement is now the estimation of a magnitude-recurrence equation. We chose the commonly used exponential relation in its logarithmic form

$$\text{Log } N = a - bM \qquad (1)$$

to represent the earthquake recurrence rate (N) for the zone as a function of magnitude (M). Other relations between N and M fit the observed data equally well, but will lead to different extrapolations at higher magnitude. It is sufficiently well known that this equation is difficult to establish, even for highly seismic regions, but an account of these difficulties will be omitted here.

The over 200 catalogued earhquakes for the rectangular northern Appalachian zone have been assessed to provide a preliminary estimate of the recurrence relation. Emphasis has been placed on the largest of the catalogued historical earthquakes in order to assign the best available magnitude estimates. The magnitude values assigned are based on a review of catalogued historical information and on some additional contemporary newspaper reports; the most reliable available information was a maximum intensity (usually reduced from exaggerated values based on historical accounts) and/or the area over which the event was reported felt. This resulted in an estimate that seven (7) of the catalogued earthquakes had magnitudes in the half-magnitude interval centred on M5.0. It is believed that the record of M5 earthquakes is incomplete throughout the first century of records and the rate of occurrence of the last century (nominally 90 yr.) yields an estimate of 0.045 earthquakes of M 5±¼ per annum in the northern Appalachian zone. The recurrence rate of M5 earthquakes is therefore about one every two decades.

The earthquake rates at magnitudes below M5 are very difficult to establish accurately. The value of the historical accounts depends strongly on the population distribution and the era of instrumental seismology is too short to establish a recurrence rate for magnitudes in the range near M4½. However, using the past 40 years of data and a normalized rate for a full magnitude increment in the range centred on 4¼ yields a rough estimate of 0.2 earthquakes per annum at M4±¼.

The presently deployed seismograph stations can detect all earthquakes in the zone at magnitudes greater than about 3½, but this capability has not existed for the past decade; the Canadian station at Fredericton did not commence operation until 1971 and the northeastern United States stations operated sporadically during this period. A careful assessment of the instrumental capability during the past decade may result in an estimate of the recurrence rate in the range of near M3½, but this has not yet been attempted.

Thus, the assigned a-value in equation (1) depends primarily on the above estimate of the recurrence rate near M5. There are insufficient data to establish a b-value for the zone, so some average value must be adopted. For various global seismic zones observed b-values range from about 0.6 to 1.3. The observed trend is to larger b-values for oceanic areas and smaller b-values for continental areas. Values ranging from 0.6 to 0.9 have been determined for the central United States (Mississippi Valley); a value of 0.78 has been determined for eastern Canada (dominantly St. Lawrence Valley). We adopt for the northern Appalachian zone a b-value of 0.7. The M4 and M5 recurrence rates estimated above formally lead to a b-value of 0.6 but the estimates are not sufficiently reliable to accept this rather low value.

Defining the magnitude-recurrence equation in its cumulative form, the seismicity of the northern Appalachian zone will be represented by

$$\log N\ (\geq M) = 2.2 - 0.7M \qquad (2)$$

Magnitude and Distance of Design Earthquakes. The full range of seismic ground motion design parameters can only be determined from information on the magnitudes of the earthquakes that are expected to occur with certain probabilties at certain distances from the site in question. The magnitude and distance of these "design earthquakes" can be used to estimate the relative levels of strong ground motion in different frequency ranges, to estimate the expected duration of the strong ground motion, and to provide a guide in the selection of representative time histories of strong ground motion.

Equation (2) can be employed to define the annual recurrence rates for certain magnitudes within the northern Appalachian zone, but does not yield any information on the location of the earthquakes. For a site, such as Point Lepreau, near the centre of the zone, a consideration of earthquake rates in circular areas around the site can be employed to produce some "design distance" choices for selected "design magnitudes" with specified exceedence probabilities.

For N occurrences per annum of earthquakes $\geq M$ within the zone of area $A = 3.4 \times 10^5$ km^2, there will be $N\pi\Delta^2/A$ occurrences per annum of the same earthquakes within a circle of radium Δ km. There is then a probability

$$p = 1 - \exp(-NT\pi\Delta^2/A) \tag{3}$$

for earthquakes of $\geq M$ to occur at $\leq \Delta$ in T years. Some examples of the results of this procedure are shown in Table 1, which gives values of Δ for selected values of p, M and T. There is, for example, a 10^{-3} probability that an earthquake $\geq M6$ will occur at a distance of ≤ 105 km from Point Lepreau within one year.

The lower right portion of Table 1 has been omitted beause it is expected that the errors on the Δ's will be at least as large as the nominal values themselves. The results in Table 1 are, however, accepted as our best estimate of "design earthquake" magnitude and distance information that can be extracted from earthquake recurrence relation. One simple example of the uncertainty of the results is demonstrated. If the seismicity determined for the northern Appalachian zone is appropriate to only half the total area, a possibility discussed above, the a-value of equation (1) would increase correspondingly and the Δ-values in Table 1 would decrease by a factor of $\sqrt{2}$. For example, there would then be a 10^{-3} probability of an earthquake $\geq$M6 occurring at $\Delta \leq 75$ km within one year. The magnitude-distance design choices presented by Table 1 are discussed below.

The above method does not account for the influence of different earthquake recurrence rates in adjacent zones. This is not important for Point Lepreau near the centre of the northern Appalachian zone (the influence on Point Lepreau of the more seismic La Malbaie region will be described briefly below), but procedures will be developed for application to sites that are significantly affected by earthquakes in more than one zone.

Acceleration Exceedence Probabilities. The site ground motion parameter still most frequently used by engineers to set design response spectrum levels is the peak horizontal acceleration with a certain probability of exceedence, although it is increasingly being recognized that other parameters such as peak velocity and the levels of lower, but sustained, ground motion may be of equal or greater importance. Work is currently underway to establish new attenuation laws for both peak acceleration and peak velocity as a function of magnitude and distance. The present form of the acceleration law based on the most recent available strong motion records is

$$a\ (g) = 0.06\ e^{0.92M}\ R^{-1.38} \qquad (4)$$

where R is hypocentral distance in km. Writing equation (4) in general form

$$a\ (g) = a_o e^{\alpha M}\ R^{-\delta} \qquad (5)$$

and writing equation (2) in a general exponential form

$$N(\geq M) = N_o e^{-\beta M} \qquad (6)$$

where N_o is now expressed per annum per km^2, an expression can be derived for probabilities of exceedence of peak accelerations at a site within the earthquake zone. An alternative method for estimating acceleration exceedence probabilities is then available using the magnitude-recurrence equation and our implicit assumption of a uniform zone of seismicity, rather than using the historical earthquakes and their location as presently provided by what is commonly called the "EMR analysis" of earthquake risk.

Equation (4) is based primarily on western U.S. strong motion data. In the near field, to distances out to about 50 km, it is assumed to be appropriate to any region. The previously employed Milne-Davenport acceleration law would predict larger accelerations from earthquakes at distances greater than about 100 km, but equation (4) is adopted for all distances in the following calculations.

By eliminating M between equations (5) and (6) and integrating the rate of acceleration exceedence multiplied by the annular differential area from the site to an arbitrary, but distant, boundary of the earthquake zone yields

$$N(\geq a) = \frac{2\pi N_o}{(\frac{\beta\delta}{\alpha} - 2)} \left(\frac{a_o}{a}\right)^{\beta/\alpha} \frac{1}{h^{(\frac{\beta\delta}{\alpha} - 2)}} \qquad (7)$$

where h is the assumed focal depth in km. This equation gives the annual rate at which a site within the region is expected to experience a peak acceleration greater than or equal to a. Inserting the parameter values in equation (7) and assuming a focal depth of 15 km gives

$$N(\geq a) = 0.18 \times 10^{-4} a^{-1.75} \qquad (8)$$

The probability that the site will experience accelerations $\geq a$ during a period of T years is given by

$$p = 1 - e^{-TN(\geq a)} \qquad (9)$$

The results of equation (10) are presented in Table 2 as peak acceleration exceedence levels (g) for selected values of p and T. There is, for example, a 10^{-3} probability that 0.10 g peak acceleration will be exceeded at Point Lepreau in one year. The peak acceleration exceedence values in Table 2 are accepted for the present purpose. Sensitivity to variations in the parameters N_o, a_o, α, β,and δ (equation (7)) will be discussed in a later report.

Two effects are, however, noted briefly here. The assumption that the northern Appalachian seismicity is appropriate to only half the total area is equivalent to an increase of a factor of 2 in N_o in equation (7). This increases the acceleration in Table 2 by about half; e.g. there would then be a 10^{-3} probability that 0.15 peak acceleration will be exceeded at Point Lepreau in one year. The acceleration attenuation law (equation (4)) is defined for the mean peak acceleration as a function of magnitude and distance. One standard deviation of the data scatter is about a factor of two in acceleration. Using an a_o in equation (4) corresponding to the mean peak acceleration plus one standard deviation would increase the accelerations in Table 2 by a factor of 2.

With a functional dependence on magnitude and distance available for other strong motion parameters such as peak velocity, duration of strong vibratory motion, etc., a computation of exceedence probabilities for these parameters could be made in a manner similar to that shown for peak acceleration in Table 2. The peak velocity attenuation law will be available soon and this will allow velocity values at specific probabilities to be employed to independently set the level of the velocity-flat portion of the design response spectrum.

Design Considerations. The seismological input information for the results presented consists of the two equations, (2) and (5), for the magnitude-recurrence rate and the peak acceleration attenuation. Accepting these two equations as the best available estimates, a choice is presented for selection of the seismological parameters for design considerations.

The results presented in Tables 1 and 2 represent expected occurrences for a site near the centre of the defined northern Appalachian earthquake zone. There are essentially two ways in which these "expected" results can be employed in a "conservative" manner for purposes of nuclear power plant design. The first choice for conservatism is straightforward: it is simply a choice of the expected seismic ground motion exceedence values at a conservatively low probability of occurrence. With this probability specified, one would simply compute, in a manner similar to that shown for peak acceleration above, a set of probabilistic ground motion parameters to be employed for plant design. This would require functional relationships for each of the desired parameters. The second choice, and the preferred method, is a judgemental selection of design parameters on the basis of the computed probabilistic results, although the resulting degree of conservatism would be unspecified.

A judgemental selection of design parameters for Point Lepreau might proceed in the following manner. A point of departure could be the M-Δ pairs for a 10^{-3} probability in one year shown in Table 1, equivalent to a 5 per cent cumulative probability of exceedence over a nuclear plant lifetime of 50 years. As the M-Δ pairs represent a type of "double-exceedence", i.e. $\geq M$ at $\leq \Delta$, a subjective choice could be to design for the seismic ground motion resulting from an M5 earthquake at an assumed focal depth directly under the site, an M6 earthquake at an epicentral distance of about 20 km, and an M7 earthquake at an epicentral distance of about 100 km. One would also consider the Point Lepreau ground motions produced by a large earthquake in the La Malbaie area. The recurrence rates for the La Malbaie zone have not yet been determined, but assuming the largest earthquake is M8 the influence of this earthquake at a distance of about 400 km would also be considered in the selection of the full range of ground motion design parameters.

Assuming a focal depth of 15 km and using equation (5), the M5, M6, M7, and M8 earthquakes described above would produce peak accelerations of 0.14, 0.18, 0.065 and 0.024 g, respectively, at Point Lepreau. The previous Milne-Davenport acceleration attenuation law, which will likely be retained for eastern Canada at large distances, predicts peak accelerations of about 0.07 g for the M7 and M8 earthquakes. This procedure produces one set of design parameters for the four design earthquakes, although it is unlikely that the peak accelerations due to the M7 and M8 earthquakes would be of any consequence in plant design. The selection of other design parameters associated with the four design earthquakes would proceed using the best available functional or empirical dependence of each of the parameters on magnitude and distance.

Although it is now clearly recognized that peak acceleration is only one of a number of important seismic ground motion parameters required for earthquake-resistant design of nuclear power plant structures and components, the procedures for estimating the other parameters are at present quite inadequate. In order that the CSA Standard N289 code for seismic design requirements for

CANDU nuclear power plants be as up-to-date as possible in this time of rapid developments in earthquake engineering, it will be necessary for the nuclear power plant engineering community to clearly define the types of seismic ground motion that would be most hazardous to the plants, and for the seismological community to develop as rapidly as possible the relationships required to estimate the ground motion parameters, and give some indication of the range of uncertainty in the estimates.

Table 1. Probability, p, of earthquakes ≥M occurring at ≤Δ km (nominal values rounded to the nearest 5 km) from Point Lepreau during time T years.

p	≥M	T (yr.)				
		1	10	25	50	100
10^{-2}	4	Δ≤65	20	15	10	5
	5	145	45	30	20	15
	6	330	105	65	45	35
10^{-3}	5	45	15	10	5	5
	6	105	35	20	15	10
	7	235	75	45	35	25
10^{-4}	5	15	5	-	-	-
	6	35	10	-	-	-
	7	75	25	-	-	-

Table 2. Probabilities, p, of peak accelerations $\geq$ a(g) at Point Lepreau during time T years.

p	T (yr.)				
	1	10	25	50	100
10^{-1}	a$\geq$.0070	.026	.044	.065	.098
10^{-2}	.027	.10	.17	.25	.37
10^{-3}	.10	.38	.63	-	-
10^{-4}	.38	-	-	-	-