SEISMIC RISK AT GROS CACOUNA, QUEBEC

by

Sheldon H. Zemell and Bassem M. Eid
FENCO ENGINEERS INC., Toronto

ABSTRACT

By means of the Cornell method, a site-specific seismic risk analysis is performed for Gros Cacouna, which had been selected as a potential site for an LNG Receiving Terminal. To ensure that public safety is maintained at an acceptable level, its relationship to seismic risk is employed to demonstrate that the latter is of the order of 10^{-3} per annum for this particular site. Although several earthquake source zones are included in this study, nearby Charlevoix dominates all others. Three different models of the spatial extent of this source are considered and its largest historical magnitude is reexamined. Ground motion at Gros Cacouna is described in terms of peak horizontal acceleration and velocity, whose attenuations are presumed to be given by the formulae of Hasegawa et al., modified in the near-field. By treating attenuation stochastically as being lognormally distributed with $\sigma = 0.7$, peak ground-motion parameters are calculated for a range of annual risk levels between 10^{-4} and 10^{-2}.

INTRODUCTION

One of the potential sites in southeastern Canada for the LNG Receiving Terminal of the Arctic Pilot Project has been identified near Gros Cacouna, Quebec. The safety of such a terminal depends to a great extent on a thorough consideration of the risks posed by human beings (e.g., sabotage, collision of a ship with the dock, operator error) and natural phenomena (e.g., winds, ice, earthquakes). The objective of this paper is to quantify, in probabilistic terms, the potential for severe ground motion due to earthquakes at Gros Cacouna.

To measure seismic risk, the technique introduced by Cornell (1) is utilized herein. In this approach, there are three distinct steps: zones of uniform earthquake occurrence are identified, magnitude recurrence curves are developed, and risk estimates are obtained by summing over the various seismic sources.

The site, approximately 10 km downstream of Rivière-du-Loup, is located at 47.94°N, 69.51°W. Because of its strength and proximity to

Gros Cacouna, the Charlevoix (CHV) zone of earthquake occurrence is responsible for virtually all of the risk. As shown in Fig. 1, the epicentres in CHV are located in the St. Lawrence River and on the north shore. Stevens (2) has reexamined the locations of some larger events near La Malbaie and relocated these near to Ile aux Coudres and Ile aux Lièvres. Several field studies (3, 4, 5) have demonstrated the existence of a microearthquake zone between these two islands. On the basis of historical seismicity patterns, Stevens' findings and the microearthquake activity, three alternate zonations of Charlevoix are considered.

In this paper, a critical consideration is the evaluation of the maximum possible magnitude, M_x, for Charlevoix. This question is directly linked to the estimation of the largest historical magnitude, displayed as $M7.7$ in the earthquake catalogue. It is contended that this magnitude is based on an overestimation of the Modified Mercalli (MM) epicentral intensity of the earthquake occurring on February 5, 1663.

The attenuation formulae of Hasegawa et al. (6) are employed to assess peak horizontal acceleration and velocity at Gros Cacouna. Being invalid in the near-field of large earthquakes, they are modified in this region, after due consideration of recent strong-motion data and relations for the western United States. Uncertainty in attenuation is represented by the lognormal probability distribution.

In CSA Standard Z276-M1981, two design levels of ground motion are defined: operating basis earthquake (OBE) and safe shutdown earthquake (SSE) with annual exceedence probabilities of 2.1×10^{-3} and 10^{-4}, respectively. Their usefulness in an assessment of public safety is limited by the omission of any allowance for population distribution in the surrounding area. To overcome this, a seismic risk consistent with an acceptable level of public safety is developed. Peak ground-motion parameters are computed for annual risks between 10^{-4} and 10^{-2}. Significant risk contributors are identified.

EXTENT OF CHARLEVOIX ZONE

Seismicity is modelled by zones characterized by uniform spatial and temporal probability of earthquake occurrence. These zones are defined on the basis of geological and tectonic considerations, together with judgment of historical earthquake distributions. On the basis of perceived concentrations of seismicity, Basham et al. (7) have defined certain zones. With reference to Fig. 1, CHV, Lower St. Lawrence (LSL) and Northern Appalachian zones (NAP) evidently have the greatest influence on seismic risk at Gros Cacouna. Because of the closeness of Gros Cacouna to CHV, which is the historically most seismically active area in eastern Canada, it is clear that risk contributions from this zone will dominate all others. In 1925 this zone experienced the only earthquake of magnitude 7 on land in eastern North America in this century.

After studying certain larger twentieth century earthquakes, Stevens (2) has concluded that their epicentres were near Ile aux Coudres and Ile aux Lièvres. Although there is no definitive explanation of these epicentral concentrations, it is speculated that the combination of the Charlevoix impact crater and Logan's Line might produce foci of stress concentrations where larger earthquakes occur. Lying between these islands is a region of high microseismicity as established by (3, 4, 5). It is approximately 30 x 90 km, with all events occurring in the Precambrian beneath Logan's contact and not in the overlying wedge of Paleozoic sediments.

To account for the spatial extent of CHV, in view of the foregoing considerations, three representations are investigated: extended, confined and semi-confined. The former is a straightforward representation of the historical seismicity, as shown in Fig. 1, with an area of 8,800 km^2. In the confined model, only Stevens' two small epicentral regions, whose total area is 1,600 km^2, are considered. The semi-confined zone, based on the recorded microearthquake activity, consists of the confined model, agumented by the intermediate region. Its area is 3,300 km^2. For the semi-confined representation, peak ground-motion parameters turn out to be some 10% greater than those of the extended model for the same probability. Furthermore, the confined model is even slightly more conservative.

Despite being the least conservative model of CHV with respect to seismic risk at Gros Cacouna, the extended Charlevoix zone is utilized in the probabilistic analysis of this study. The principal motivation for this decision is that the extended model provides the closest correspondence to the historical seismicity. Additionally, subsequent conservative assumptions about attenuation of ground motion may be offsetting.

MAXIMUM MAGNITUDE

The upper bound M_x to the size of an event in an earthquake zone is often taken equal to the largest historical magnitude plus a safety margin (0.5 to 1.0) which decreases as the number of years of complete detection of large events increases. For the Charlevoix zone, with its long observational period, the safety margin can be assumed to be 0.5. This is added to the magnitude of the great 1663 earthquake, rounded to the nearest half-unit.

According to the earthquake catalogue, the only three known events in the Charlevoix zone whose estimated magnitudes are 7 or greater are as follows: M7.7 in 1663, M7.0 in 1870 and M7.0 in 1925. Because of the sparsity of settlements in the surrounding region at the time of the first of these shocks, there is considerable uncertainty about the presumed size (and location) of this earthquake. It is worthwhile to review this event in light of our current knowledge of seismicity in eastern Canada.

The principal original accounts of this earthquake appeared in the Jesuit Relations. It was noted that property damage was relatively minor and there was no loss of life. These accounts are consistent with a Modified Mercalli intensity of *VI*, which was the intensity experienced in the same area during the 1925 earthquake of magnitude 7.

The occurrence of vast landslides along the St. Maurice, Batiscan and St. Lawrence Rivers was felt to be further evidence of the severity of this earthquake. However, Hodgson (8, 9) has emphasized that the marine clays in this part of Canada are extremely susceptible to landslides when they are subjected to long periods of rain. Indeed, landslides can be generated in this area with or without earthquakes.

This earthquake was felt over the entire eastern part of North America. For instance, there were reports of chimneys being broken and pewter being jarred from shelves in the Massachusetts Bay area. These effects would be described locally by an *MM* intensity of *V* or *VI*, which is consistent with the intensity thereat assigned for the March 1, 1925 event in (10). In addition, the well-known weak attenuation of seismic waves in eastern North America accounts for the widespread felt area of this shock.

Although Hodgson (8) remarked that the epicentral intensity of the 1663 shock was not markedly greater than other earthquakes (e.g., the ones of 1870 and 1925) in the same area, it has been assigned a maximum intensity of *X*, equivalent to a magnitude 7.7, by Smith (10). Unfortunately, the *MM* scale groups severe structural damage with landslides as intensity *X*. According to the foregoing argument, a maximum intensity of *X* overestimates the size of this shock, and a lower maximum intensity of *IX* (say) is more appropriate. Thus, the largest historical event for CHV is $M7.0$, so that the maximum magnitude M_x is taken as 7.5.

ATTENUATION

Peak horizontal acceleration and velocity are selected as representative ground-motion parameters. In the vicinity of Gros Cacouna, their attenuation is presumed to be governed by relations appropriate to eastern Canada in (6). Because of the large dispersion of ground-motion measurements, for the same magnitude and hypocentral distance (e.g., see (11, 12)), the attenuation formulae are to be viewed as median relations. For eastern Canada, peak horizontal acceleration a (%g) and peak horizontal velocity v (cm/s) are given by:

$$a = 0.34 \exp(1.3M)\, R^{-1.1}$$

$$v = 0.00018 \exp(2.3M)\, R^{-1.0}$$

with R being focal distance in km. A standard depth of 18 km is presumed for the foci of earthquakes.

These attenuation formulae have been derived by means of regression analysis based on available strong-motion data for the western United States. Because of the paucity of strong-motion near-field data, their use should be restricted accordingly. Since it is clear that relatively large events near the site will contribute significantly to seismic risk thereat, such inaccuracies in attenuation relations will lead to misestimations of risk.

The aforementioned data deficiency has abated somewhat following the release of records for the 1979 Coyote Lake and Imperial Valley earthquakes in California. These data permit the extension of attenuation relations to small hypocentral distances as in (11, 12). Unfortunately, a direct comparison between these formulae and those of Hasegawa et al. for western Canada is difficult to effect because of the utilization of different distance metrics and magnitude scales. Nevertheless, it appears that the magnitude dependence of Hasegawa et al. differs substantially from other authors, so that peak horizontal acceleration predictions for larger magnitudes are greater at <u>all</u> distances, not merely in the epicentral area. On the other hand, the foregoing peak velocity formula generally predicts lower results than those of (11), say; but, both appear to be too high in the near-field, in view of the available data.

The near-field portion of the eastern Canada peak acceleration formula is modified by flattening the curves at a hypocentral distance of <u>40 km</u>. The same modification is applied for peak horizontal velocity. This particular distance (40 km) is selected in a probabilistic risk model for Charlevoix since the hypocentral range between 18 km and 40 km is approximately bisected by the attenuation curves for $M = 7.5$ given by Hasegawa et al. (6) and Joyner et al. (11).

Hitherto, the dispersion implicit in the attenuation formulae has been neglected. In fact, median relations have been developed from the empirical distributions Y of peak acceleration and velocity, which are approximately lognormal, so that the amount of dispersion is proportional to the median value $\overline{Y}$. Thus, the stochastic form of the attenuation formulae can be written in the form proposed by Merz and Cornell (13):

$$Y = \overline{Y}E$$

where $Z = \ln E$ is Gaussian with mean 0 and standard deviation σ. Typically about 70% of the distributed $\ln Y$ values are within ± 0.7 units of the mean value of $\ln Y$; i.e., one standard deviation of the distribution of $\ln Y$ is approximately 0.7.

SEISMIC RISK RESULTS

At the low levels of risk considered, there is no practical difference between seismic risk, in terms of the per annum probability of exceedence of some measure of ground-motion, and the average annual number of exceedences thereof. For any measure, y, of ground-motion, the number of annual exceedences due to a small source of area dA is a function of the seismicity (i.e., the magnitude recurrence relation) and the hypocentral distance R.

For each seismic source zone near a site, the annual frequency of earthquakes greater than any magnitude M can be described by an empirical relation of the form $N(\geq M) = N_O \exp(-\beta M)$, along with an imposed maximum possible event M_x. By means of Weichert's application of the method of maximum likelihood (14) to the earthquake data for the zones shown in Fig. 1, their magnitude recurrence parameters N_O and β are estimated. Because of the overwhelming dominance of CHV, only its results are given herein; viz., $N(\geq M) = 305 \exp(-1.61\ M)$, with $M_x = 7.5$.

A formula for the mean annual number of exceedences of $Y = y$ due to a seismic source area dA is given in (15), if attenuation is lognormally distributed. It can be shown that the number of exceedences increases with the standard deviation σ of $\ln Y$. Such risk contributions are summed over all source elements to produce the total seismic risk at Gros Cacouna.

In the Introduction, various possible design levels were mentioned. There included probabilities of 2.1×10^{-3} and 10^{-4} per annum, corresponding to the so-called OBE and SSE, respectively. In addition, a site-dependent level linked to a separate public safety analysis is developed hereunder.

Let A be the event that a specified level of ground motion is exceeded at the site during a given year; let B be the event that an exposed individual in the region surrounding the plant perishes, given that A has taken place; and let C be the occurrence that a particular exposed person becomes a fatality in a definite year due to seismic phenomena. Then, if $P(X)$ denotes the probability of an event X, it is clear that

$$P(C) = P(A)\ P(B)$$

provided that there are no earthquake-related deaths if the ground motion is less than the specified level in the definition of A. In the public safety statement, it was noted that a risk level of 10^{-6} per person per annum is acceptable to the general public. By considering the probabilities of catastrophic failure of critical structures after event A, wind direction, population distribution, locations of ignition sources, and other factors, $P(B)$ was estimated to be of the order of 0.5×10^{-3}. Since all other risk components sum to approximately 0.5×10^{-6}, then $P(C)$ can be equally large. Thus, a seismic risk of 10^{-3} for this site yields an acceptable public risk.

A computer program is employed to perform a numerical integration over all relevant source areas in order to determine seismic risk at the site. The results for peak horizontal acceleration and velocity, are summarized in Tables 1 and 2, respectively. In Fig. 2, the estimates of peak acceleration corresponding to per annum risks between 10^{-4} and 10^{-2} are displayed.

The near-field modification of the attenuation relations has a significant effect on these estimates. For instance, the formulae of Hasegawa et al. (6), extrapolated into the near-field, would yield about 200%g and 200 cm/s, in the case $\sigma = 0.7$ at the 10^{-4} level.

As an initial step prior to constructing site-dependent response spectra, distances of significant sources must be ascertained. The computer printout establishes that CHV is responsible for virtually all of the risk for the levels investiated at Gros Cacouna. There are significant risk contributions within CHV from between 10 km and somewhat over 70 km from this site.

SUMMARY

Seismic risk estimates are developed for Gros Cacouna by means of Cornell's probabilistic method (1). The analysis is dominated by the nearby (about 10 to 20 km) Charlevoix zone, the most active earthquake area in eastern Canada. The largest historical event in CHV occurred in 1663. After a reevaluation of this event, it is estimated to have been of magnitude 7.0; this, in turn, leads to a maximum possible magnitude M_x of 7.5. Seismicity in CHV is represented by the extended model which reflects the presumed locations of historical epicentres.

Peak acceleration and velocity estimates are developed by means of the attenuation relations of Hasegawa et al. (6), modified in the near field. This modification, inspired by western United States earthquake data and relations, consists of flattening the curves within a hypocentral radius of 40 km. It is proposed that seismic design levels be based on the OBE and a site-dependent level consistent with an acceptable public risk; for Gros Cacouna, the latter seismic risk is 10^{-3} per annum, for which peak parameters are 62%g and 54 cm/s.

REFERENCES

1. Cornell, C.A., "Engineering Seismic Risk Analysis," Bull. Seism. Soc. Am., Vol. 58, 1968, pp. 1583-1606.

2. Stevens, A.E., "Reexamination of Some Larger La Malbaie, Quebec Earthquakes (1924-1978)," Bull. Seism. Soc. Am., Vol. 70, 1980, pp. 529-557.

3. Leblanc, G., Stevens, A.E., Wetmiller, R.J. and Duberger, R., "A Microearthquake Survey of the St. Lawrence Valley near La Malbaie Quebec," Can. J. Earth Sci., Vol. 10, 1973, pp. 42-53.

4. Leblanc, G., and Buchbinder, G., "Second Microearthquake Survey of the St. Lawrence Valley near La Malbaie, Quebec," Can. J. Earth Sci., Vol. 14, 1977, pp. 2778-2789.

5. Anglin, F.M., and Buchbinder, G., "Microseismicity in the Mid-St. Lawrence Valley Charlevoix Zone, Quebec," Bull. Seism. Soc. Am., Vol. 71, 1981, pp. 1553-1560.

6. Hasegawa, H.S., Basham, P.W., and Berry, M.J., "Attenuation Relations for Strong Seismic Ground Motion in Canada," Bull. Seism. Soc. Am., Vol. 71, 1981, pp. 1943-1962.

7. Basham, P.W., Weichert, D.H., and Berry, M.J., "Regional Assessment of Seismic Risk in Eastern Canada," Bull. Seism. Soc. Am., Vol. 69, 1979, pp. 1567-1602.

8. Hodgson, E.A., "The Marine Clays of Eastern Canada and Their Relation to Earthquake Hazards," J. Roy Astron. Soc. Can., Vol. 21, 1927, pp. 257-264.

9. Hodgson, E.A., "The Probable Epicentre of the St. Lawrence Earthquake of February 5, 1663," J. Roy. Astron. Soc. Can., Vol. 22, 1928, pp. 325-334.

10. Smith, W.E.T., "Earthquakes in Eastern Canada and Adjacent Areas 1534-1927," Pub. Dom. Obs., Vol. 26, 1962, pp. 271-301.

11. Joyner, W.B., Boore, D.M., and Porcella, R.L., "Peak Horizontal Acceleration and Velocity from Strong-Motion Records." Seism. Soc. Am. Earthquake Notes, Vol. 52, 1981, pp. 80-81.

12. Joyner, W.B., and Boore, D.M., "Peak Horizontal Acceleration and Velocity from Strong-Motion Records Including Records from the 1979 Imperial Valley, California, Earthquake," Bull. Seism. Soc. Am., Vol. 71, 1981, pp. 2011-2038.

13. Merz, H.A., and Cornell, C.A., "Seismic Risk Analysis Based on a Quadratic Magnitude-Frequency Law," Bull. Seism. Soc. Am., Vol. 63, 1973, pp. 1999-2006.

14. Weichert, D.H., "Estimation of the Earthquake Recurrence Parameters for Unequal Observation Periods for Different Magnitudes," Bull. Seism. Soc. Am., Vol. 70, 1980, pp. 1337-1346.

15. Cornell, C.A., "Probabilistic Analysis of Damage to Structures under Seismic Loads," in Dynamic Waves in Civil Engineering, Howells, D.A., Haigh, I.P., and Taylor, C., Editors, John Wiley, London, 1970.

TABLE 1: Peak Horizontal Acceleration (%g)

Per Annum Risk	σ	
	0.0	0.7
10^{-2}	13	16
2.1×10^{-3}	30	45
10^{-3}	40	62
10^{-4}	80	150

TABLE 2: Peak Horizontal Velocity (cm/s)

Per Annum Risk	σ	
	0.0	0.7
10^{-2}	5.2	6.3
2.1×10^{-3}	26	32
10^{-3}	40	54
10^{-4}	95	170

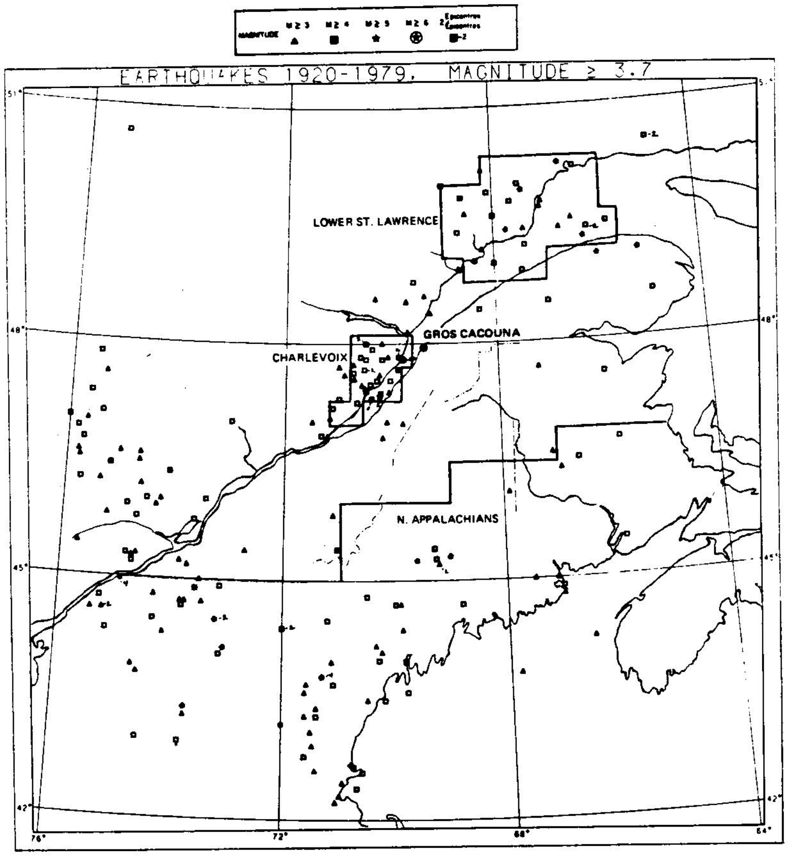

FIG. 1. Historical Epicenters and Zones of Earthquake Occurrence near Gros Cacouna

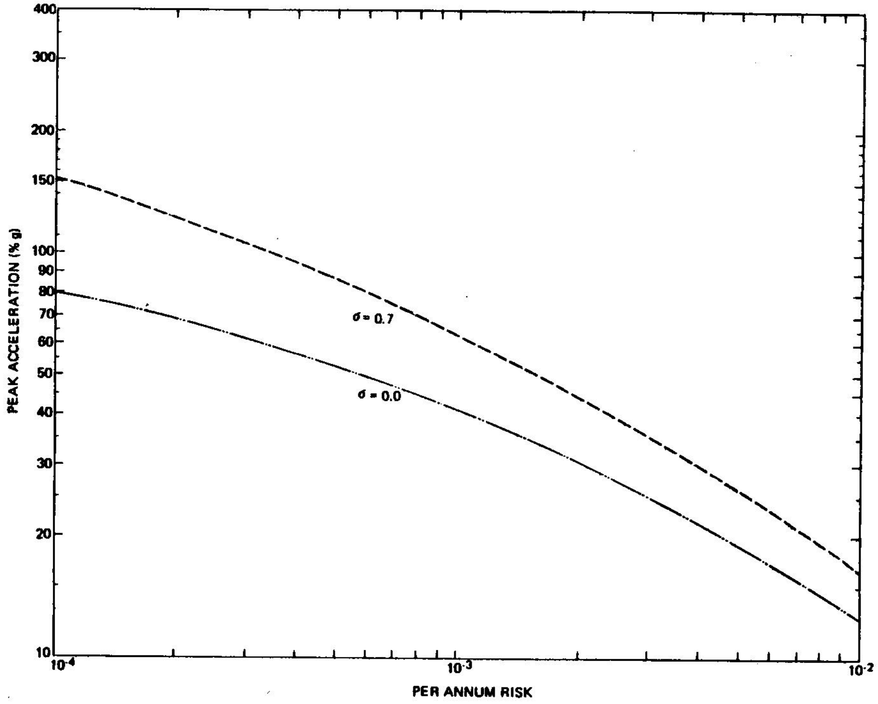

FIG. 2. Peak Horizontal Acceleration versus Risk