SEISMIC RISK OF THE QUEEN CHARLOTTE ISLANDS AND ADJACENT AREA

D.H. Weichert, G.C. Rogers, R.D. Hyndman and R.B. Horner
Pacific Geoscience Centre, E.P.B., Sidney, B.C., V8L 4B2, Canada

Abstract

The current favoured method of seismic risk estimation for most areas of Canada, at risk levels of 10% in 50 years, is a Cornell-type approach. The method employs seismogenic zones with uniform spatial and temporal activity, over area and point source models for the earthquake and an exponential groundmotion-magnitude relation saturating at magnitude 7.5. The Queen Charlotte (QC) seismic zone is the one area in Canada where earthquakes are clearly correlated with a major fault and where the large magnitudes (8.5) and aftershock distributions imply significant fracture lengths. The simple point source model is therefore not adequate, and limits to ground motion become important. The latter reduce the nominal maximum magnitude of M8.5 for this zone effectively to about M8.0. A finite-length fault source model allows more distant earthquakes to propagate into the vicinity of a given site and results in probabilistic groundmotions that are factors of about two higher than the standard Canadian model. However, the necessary additional assumptions on the unknown statistical distributions of dynamical fault source parameters introduce considerable uncertainty. A re-evaluation of early earthquake records shows that almost all major seismicity occurs on the QC fault. Regardless of the statistical procedures used, this reduces the risk at mainland sites, such as Prince Rupert, significantly. At least one seismic gap appears to exist along the QC fault at present, and a statistical model of strain buildup seems to confirm the potential for a magnitude 7.5 earthquake. Ground motion for such an event is within the long-term risk estimates at a level of 10% in 50 years in the central QC island area.

INTRODUCTION

Over the past few years, research at the Earth Physics Branch (EPB) has been directed toward a new scheme of mapping seismic risk for purposes of recommending changes to be incorporated in the 1985 version of the seismic zoning map of Canada. Seismic risk provisions have been included in the National Building Code of Canada since its first edition in 1953. The first qualitative risk map was replaced in the 1970 code edition by a quantitative probabilistic map of peak horizontal ground acceleration, which is still in force today. The new approach (1,2,3,4) is based on a suggestion made by Cornell (5) and a computer program by McGuire (6). Briefly, seismic source zones of assumed uniform activity are defined by a judgemental procedure based on observed seismicity patterns and geological-geophysical information. Recurrence relations for each source zone are calculated; they are expressed as seismic activity, a recurrence slope, and a deterministic maximum magnitude. Relations connecting groundmotion parameters, earthquake magnitude and distance from a given site are then used to calculate the average frequency of exceedence of a given groundmotion, i.e. peak horizontal acceleration as in the past, and velocity as an additional parameter for incorporation in the 1985 Code. The procedure works well for most areas of Canada, where a model of point source earthquakes distributed uniformly throughout source zones can be justified. This is not the case in the QC area, where most seismic activity occurs along a well-defined fault and where very large earthquakes are known to have occurred. The increasing industrial developement along the Canadian northwest coast and the suggested petroleum potential of the QC Sound area are now creating a demand for special risk studies, and this paper is an attempt to outline some constraints.

This paper presents the relevant current knowledge of seismicity and seismotectonics in the QC area and relates it to the new seismic risk estimates that are being recommended for adoption into the National Building Code of Canada. It then examines the method used by EPB to allow for the limit to groundmotions at large magnitudes; another refinement is introduced , which utilizes a fault model instead of a point source model. Finally, the consequences on risk of an earthquake filling the observed seismicity gap south of the QC Islands, and the question of time-variable risk is considered.

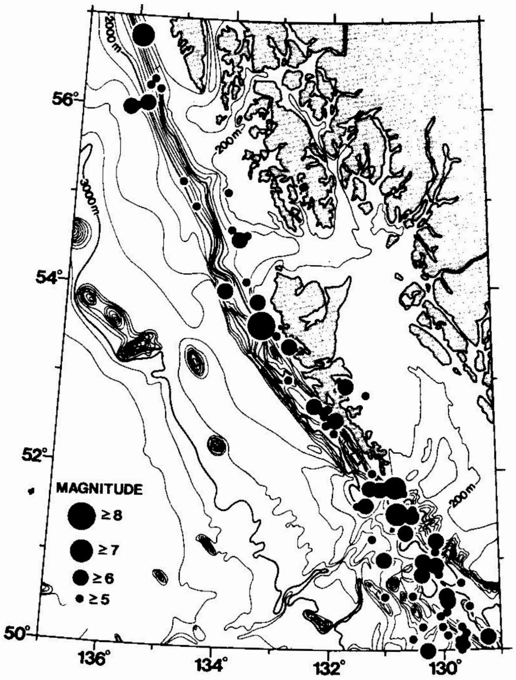

Figure 1. Epicenter plot from EPB data file of all located events in QC area of magnitude greater than M5, with the revisions from Rogers(10)

SEISMICITY

The QC Islands, Hecate Strait and QC Sound with Vancouver Island comprise the Insular Belt of the Canadian Cordillera (7,8), an assembly of exotic crustal fragments or terranes from far southerly latitudes that accreted to the North American continental margin during the Mesozoic (70 Ma years and earlier). At the present time, the main boundary between the North American and Pacific lithospheric plates follows the QC fault north of 52°N. South of the QC Islands, there is a triple point with a convergence or subduction zone to the southeast along the Vancouver Island margin and the Juan de Fuca spreading ridge system to the southwest (9).

Almost all known seismicity in the area appears to occur near the plate boundary, as shown in Figure 1. The major difference of this seismicity plot from the one given by Milne et al.(9) is the relocation of several large early instrumentally-located earthquakes from QC Sound and Hecate Strait onto the QC fault. This was accomplished by a thorough search for additional data, re-interpretation of seismic phases in the light of new experience as well as the use of a modern computer epicenter routine. However, depending on the time of occurrence and magnitude of the earthquake, the location accuracy still varies from about 30 to 50 km. Only 2 epicenters of earthquakes of magnitude greater than 5 appear to lie east of the QC fault, but both are within the error estimate of being on the fault.

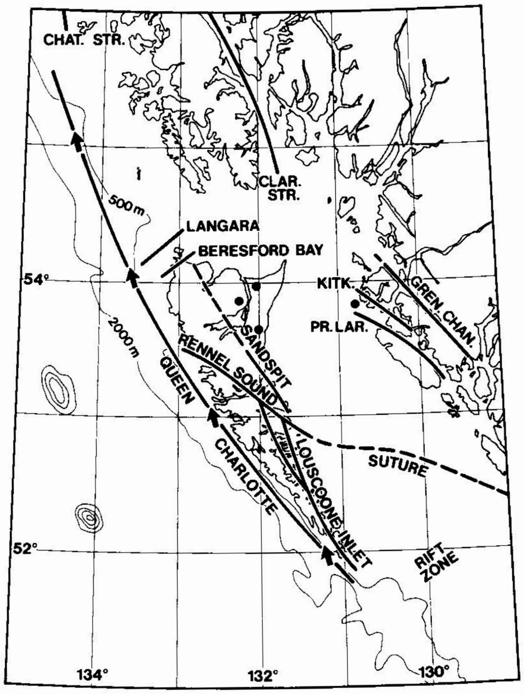

Figure 2. Regional geological map of the QC area showing the major faults. The four epicenters shown are well-located recent earthquakes of magnitudes 3 to 4. Fault name abreviations:

CHAT.STR.-Chatham Strait;
CLAR.STR.-Clarence Strait;
GREN.CHAN.-Grenville Channel;
KITK.-Kitkatla;
PR.LAR.-Principe Laredo.

The arrows on the QC fault represent motion of the Pacific Plate relative to N-America plate.

Figure 2 shows a map of the known faults inland from the QC fault. Superimposed are four recent well-located earthquakes with magnitudes 3.3

to 4.2. They do not coincide with any major mapped fault, but are near enough to the Sandspit and the Kitkatla or Principe Laredo faults, to suggest ongoing activity. The Sandspit and Rennell Sound faults appear to be part of the (ca.140 Ma old) suture between two of the accreted terranes of Yorath and Chase (11), who also proposed that rifting, in QC Sound during the Early Miocene, resulted in dislocation along the Sandspit and Louscoone Inlet faults. In their model, major recent motion is not suggested on the Sandspit fault. Obviously, much more data will have to be collected to differentiate between any possible activity on these coastal faults and general low level background seismicity, as seen throughout the Cordillera. The EPB Skidegate seismic station has not revealed any significant number of small seismic events east of the main QC fault. During 1982, EPB has installed 3 additional regional seismic stations in the area, in order to improve detection and location thresholds.

For purposes of seismic zonation, EPB (4) has represented the seismicity in this area by 2 zones, the QC and the Sandspit source zones. The QC zone is a strip of about 50 km width that is centered on the QC fault and follows it from the triple junction near 52°N to 57°N from where the Fairweather-Yakutat zone continues. Inland from the QC zone, all seismicity was lumped into the Sandspit zone which adjoins the QC zone as a strip of similar width. The width of the QC zone represented the uncertainty in the epicenter location. The seismic activities in the two zones did not reflect all of the most recent epicenter relocations, so that a further small reduction of the Sandspit zone activity may be warranted.

Near the south end of the QC Islands, Figure 1 shows a gap in seismicity at the level of plotted magnitudes, M5. No major earthquake has occurred in this region since the turn of the century and modern data show that this region is almost aseismic at more moderate magnitude levels as well (12,13). An earthquake of about magnitude 7.5 would be required to fill the gap completely; however, the fault may move aseismically in this area. Near the north end of the islands, another gap may exist, but its reality is open to some interpretation(13).

SEISMIC RISK ESTIMATION

Effect of Earthquake Relocations. The earthquake relocations described above have an obvious effect on seismic risk at places on the mainland such as Prince Rupert. The removal of major earthquakes from QC Sound and Hecate Strait to the QC fault increases the distance to the mainland, thus decreases expected groundmotion, especially the high frequency accelerations. The current Supplement of the National Building Code of Canada, Table J-1, which is still based on the pre-1970 data set, lists the peak horizontal acceleration for Prince Rupert at 0.01 per annum exceedance probability as 11.3 % of gravity. Identical statistical calculations with the revised data set now give only about 7 %g for the area. This has caused some difficulty for engineers who have received site specific calculations (extreme value A-100) from EPB during the last few years.

The current approach to risk estimation no longer accounts for individual earthquakes directly, but distributes their effect over their respective source zones. The risk estimates may therefore not be identical, but must be similar to the earlier method. Figure 3 shows the estimated peak ground acceleration calculated by the new method for the Prince Rupert area as a function of the annual risk. The 7.5 % g of the standard model, at a probability of 0.01 per annum compare well with the older calculation: this confirms that the lowered risk, or lowered acceleration, at Prince Rupert in not an artifact of the new procedures but is a result of new data. Smaller differences can be explained by re-evaluation of the relationships between groundmotion - magnitudes and distances (14).

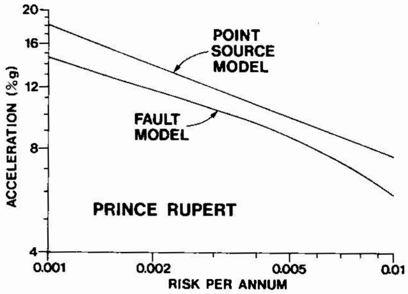

Figure 3. Peak horizontal ground acceleration estimates as function of per annum risk for new standard EPB risk model and a fault risk model.

Change of Probability Level. Another change recommended for the 1985 NBC edition is a change of the standard risk level from the so-called 100-year event to a 475-year event. This corresponds to a 10% probability of exceedence in 50 years, or 0.002105 per annum. The groundmotion from one risk level to the other is roughly proportional to the square root (0.5 power) of the risk, but varies across the country. For this site, one obtains a 0.4-power relation from Figure 3.

Upper Limits to Ground Motion. A criticism that has been raised against the groundmotion - magnitude - distance relations used by EPB (14) is their unlimited increase with magnitude. Thus, acceleration is made to increase as exp(1.3M), and velocity as exp(2.3M), where M is the local magnitude. However, it is generally accepted that high frequency groundmotion saturates somewhere in the range near M7.0 or M7.5. This is a consequence of the shift of the dominant energy to lower frequencies, as the earthquake size increases. It has been argued (1,2,14) that this saturation is relatively unimportant in many areas of Canada, where maximum magnitudes range from 6.5 to 7.5. In the QC area, a realistic maximum is M8.5, and here it appears imperative to introduce some upper bound into the groundmotion relations. Thus, groundmotions are restricted to the effects of magnitude 7.5 earthquakes, which is achieved by concentrating the expected number of greater earthquakes as a spike at M7.5 in the recurrence density. Other valid choices are: the extra number of M7.5 earthquakes (comprising the spike) could be made to have a total moment, or energy, equal to that of the larger earthquakes; or the groundmotion relation could be limited instead of the event number relation. All such choices should give groundmotions between those for a maximum magnitude 7.5 and the adopted 8.5. In fact, the adopted constraint gives accelerations about 1.5 times higher than an $M_{max}7.5$, and 1.5 times lower than $M_{max}8.5$, i.e. it lowers the deterministically set $M_{max}8.5$ to an effective M8.0. Unfortunately, a missing dimension in these calculations is still the increase of the duration of strong ground motion with magnitude. The point source model described so far will in the sequel be considered the (EPB) standard model.

A Fault Source Model. The described constraint on groundmotion falls somewhat short of the real differences between a point source earthquake and the effects of a M8.5 earthquake rupturing over several hundred kilometers. The large-scale broadband ground motion effects of such an earthquake are related to its overall averages of displacement, shear coefficient and fault area. On the other hand, the large amplitude, high frequency groundmotion components with periods shorter than about 1 second important for most buildings, are thought to be caused by the individual breakage of asperities, distributed in some unkown way along the fault. This is the justification for modelling large earthquakes as a series of smaller ones for risk estimation. The next logical refinement would be a distribution of these earthquakes along the fault. Whilst such a model would move some energy release centers further away from a given site it would also allow for the possibility of a distant earthquake to propagate into closer vicinity of a site. The tradeoff does not appear to be intuitively clear.

A fault risk model has been in the literature for some years (17) and a computer program exists (18). The reason for EPB not utilizing such an approach for Canadian risk estimation was its apparent limited applicability to Canadian conditions, and the belief, that the increased number of statistically uncertain stochastic parameters needed to describe the model would detract from its credibility. The following describes a comparison of such a fault risk model with representative parameters for the QC area and the earlier described standard model. First, ground motion must be described as function of magnitude and a distance. Next, the length of rupture of the fault as a function of earthquake magnitude must be taking into account.

Distance is no longer hypocentral, i.e. measured to the original fracture initiation, but to the points of high frequency energy release, i.e. to the nearest asperities. Their locations are unknown and therefore assumed randomly distributed along the fault length. The relevant distance is now taken to the nearest ruptured section of the fault. For small earthquakes, perhaps up to magnitude 6 or 6.5, rupturing fault lengths of the order of ten kilometers, this makes little difference. Because the objective of our exercise is a comparison of the effects of giving the larger earthquakes a finite extent, the same groundmotion relations as for the standard risk model have been used. Other relations found in the literature (e.g. 21) can be explored if the fault risk approach appears desirable. We use accelerations of 10 cm s^{-2} $\exp(1.3M)R^{-1.5}$, with R the nearest distance to a 20 km deep fault line, not to a fault plane surface and ground motion limited to M=7.5, as in the standard model. If a fault plane model were to be employed, some statistical distribution of elasticity parameters with depth may have to be introduced, i.e. only the deeper fault sections are expected to be strong enough to produce the large groundmotions. Just as in the standard point source model, we allow a factor of two uncertainty in the groundmotion; this is expressed as a standard deviation of 0.7 in the natural log of the acceleration, which is assumed to be normally distributed.

For the relation between fault length and magnitude, a variety of suggestions can be found in the literature (19,20). There appears to exist a clear regional difference, and we select an average from (19), near the Californian relations. This is consistent with known slip rates and magnitude recurrences along the QC fault (16). Thus, we use log L = -5.5 + 1.0M, where log L is the decimal logarithm. Several variations of this model were calculated, i.e. different uncertainties in the fault length relation and different fault segmentations, each leading to about 20% higher groundmotions than shown in Fig. 4.

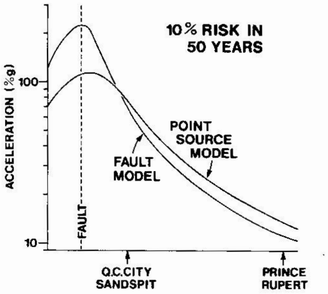

Figure 4. Peak horizontal ground acceleration profile from the QC fault on a profile through QC City area to Prince Rupert, at a per annum risk of 0.002105. The fault is described by two segments similar to (4) and the fault length relation has an uncertainty factor of 3.

Figure 4 are acceleration profiles, at a risk of 10 % in 50 years, from the QC fault in an east-northeasterly direction to about Prince Rupert. As predicted, the fault risk model and the standard model agree well at the longer distances. The slightly higher level of the standard model approaches the level of the fault model ground motion at greater distances, and can therefore be explained by the closer effective distances of Prince Rupert from the distributed standard model seismicity. The Sandspit zone has very little significance at Prince Rupert; the zone may be responsible for some noticable asymmetry in the peak of the standard curve in Figure 4, but even within its own extent, the zone only contributes about 1/10 of the ground motion at 0.002105 p.a. risk. This justifies its omission in the fault risk model, and a possible reconsideration in the standard model.

Very significant differences between the models appear near to the fault. The much larger groundmotions of the fault risk model here is partly attributable to the restraint of earthquakes to the imaginary fault line while the standard model allows a uniform spreading of epicenters over about 50 km width. Compressing the zone by factors of two only results in about 20% and 40% increases in ground motion so that the remaining increase should be attributed to the finite source lengths; however, the standard program results begin to be erratic for such narrow zones, making this comparison inconclusive.

It must be concluded that there is little difference between the two models at reasonable distances, which justifies the choice of the simpler model for routine applications. In the near field, however, a variety of assumptions break down in both models, and special studies become indispensable.

Seismic Gaps and Temporally Variable Seismic Risk. The probabilistic risk estimates have been based on average earthquake occurrence rates observed over the past 100 years or less. These averages were found to be consistent with the long term ongoing relative northwestward drift of the Pacific plate from plate tectonic models (16), thus confirming our understanding of the causative forces. One can therefore, conclude that the identified gaps in the seismicity pattern along the fault must be filled in the foreseeable future, i.e. the risk along these sections must be higher than average for a short-life structure. It may return to average over a 50 year exposure period, but such a structure would have to be built to the higher short term risk.

The gap south of the QC Islands shown in Figure 2 needs approximately a magnitude 7.5 earthquake. At Sandspit, this should produce about 10% g and 20 cm/s peak acceleration and velocity, respectively, according to (14). At Prince Rupert this should be attenuated to 5% g and 10 cm/s. If we assume a reasonable asperity model of M6.5 events filling the gap, the groundmotion decreases at Sandspit by 50%, at Prince Rupert by 80-90%. If we use a competing magnitude distance relation (21), the Sandspit groundmotion decreases another 50%. We have only one strong motion record from the 1970 M7.0 event just south of the current gap, recorded at the Sandspit airport. Both horizontal components showed an acceleration of 4 %g and the maximum velocity was 9 cm/s, giving support to the first relation when allowance is made for difference in distance and magnitude. However, the subsoil at Sandspit is deep sandy-gravel which could easily give an amplification factor of two compared to bedrock, for which the standard risk calculations are purportedly made. In any case such accelerations are well below the values obtained by the standard model at 0.002105 p.a. risk, and we conclude that at the distance of the Central QC Island area the short term risk due to the existence of the gap is not as great as the long-term risk from the standard probabilistic approach. Nearer to the expected epicenter, higher accelerations are predicted, but they would still be no greater than the effects of an M7.5.

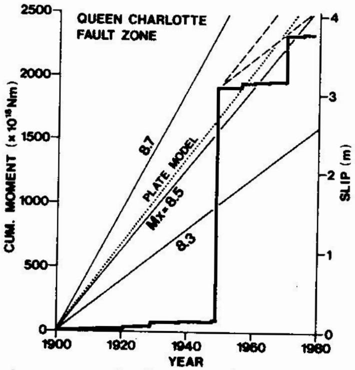

Figure 5 Estimated seismic moment release and fault slip as a function of time for the QC fault zone.

The existence of the gap since at least the turn of the century in itself only suggests the there is a significant possibility of a M7.5 event and that its probability of occurrence increases with time. Yet, the larger events cannot occur completely randomly since the earthquake process involves the slow buildup of elastic strain and a sudden release. Figure 5 shows the accumulated moment, or slip, along the QC fault since the beginning of the century, using a standard moment-magnitude relation; the build up is seen to be completely governed by the largest earthquakes. The sloping lines represent average strain release, or slip along the fault under assumptions of different maximum earthquakes. The "plate model" line corresponds to an annual motion of 55 mm, as given in (16). The sloping lines represent estimates of the minimum accumulated strain, and a significant lag of the stepped actual release supposedly indicates an increased earthquake potential. Unfortunately, one does not really know if and where in the past strain was completely relieved, so only the slope of the lines is significant. From the diagram, one can see the potential for a M7.5, but whether this would rupture the recognized gap in one earthquake or in a series of smaller ones cannot be predicted. The drawing of the lines through the highest point of the actual release plot gives the minimum strain available for release at present along the whole fault, not just along the gap.

CONCLUSIONS

Our prime objective has been a study of the applicability of the standard Canadian seismic risk model for the high risk region near the QC fault. The proposed new risk maps have 32%g and 32 cm/s as the highest groundmotion contours and we have shown that this is very reasonable in view of the extreme values and large differences between models in the near field of the fault. For the lower groundmotion levels at some distance from the fault, the estimates are sufficiently robust to model changes, and the standard point source model appears adequate but in the near field of large earthquakes, and also at very low-risk extrapolations, details of the energy release dominate. Here, special studies become mandatory and the probability concept may be difficult to maintain. As an interesting example of the model break down at low risk, we have seen how the Prince Rupert risk depends on the assumption of relative aseismicity on the Sandspit and inland faults, a reasonable assertion based on current data, but unacceptable when risks of 10^{-4} per annum are to be considered.

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