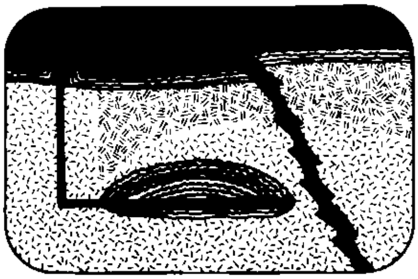

Seismic Risk and Toxic Waste Disposal: A Discussion

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Summary
Earthquakes, whether natural or induced, pose a significant risk to the disposal of toxic wastes by burial or fluid injection in the crust. Methodology exists for assessing the ambient seismic risk at moderately low levels of probability, but for greater degrees of conservatism the assessment is essentially deterministic. Such estimates are considered appropriate for periods comparable to that of the available seismic history but an improved understanding of the nature of currently active seismic zones is required for the estimates to be applied with confidence to periods of time measured in thousands of years. The potential hazards associated with this natural seismic risk can be mitigated by appropriate engineering design and practice. Induced seismicity associated with mining excavations, thermally induced stresses or fluid injection can be controlled by appropriate engineering design and operational procedure.

Introduction
One of the most challenging problems associated with our highly materialistic society is the disposal of wastes - the ultimate end product of all industrial activity. While the disposal of toxic wastes has only recently attracted significant public attention, it is now clear that a satisfactory solution is essential for the continued well-being of at least the chemical and nuclear industries. The problem touches on many aspects of the biological, environmental and earth sciences. Here we shall discuss the seismic risk and associated hazards that must be considered in the site selection and engineering design of waste disposal facilities.

When discussing the effects of earthquakes it is useful to differentiate between estimates of earthquake-generated vibratory ground motion, which we shall define as *seismic risk* and the consequences of such motion, measured in damage done, which we shall call *seismic hazard.* The point of this distinction is that for natural earthquakes the seismic risk is independent of man's activities whereas seismic hazard results largely from damage done to structures of one kind or another. The current state-of-the-art does not allow us to prevent natural earthquakes but we can, by proper engineering design, mitigate their effects and thus reduce the associated hazards to acceptable levels.

There are two classes of earthquakes: those occurring naturally and those occasionally induced by industrial activities such as mining, extraction of oil and gas, high pressure fluid injection in the crust and the impounding of large reservoirs

Ambient Seismic Risk
The assessment of ambient seismic risk has been the subject of considerable research during the past decade and this continues unabated at the present time. The degree of confidence that one can attach to a particular assessment depends upon the degree of understanding that is available of the earth processes that are generating the earthquakes, our knowledge of local seismic wave attenuation, the mathematical techniques that are used, the degree of conservatism that is considered appropriate for the project in question, and the expected lifetime of the project. The current version of the seismic provisions of the National Building Code of Canada (NBCC), for example, are based on the value of peak acceleration that is expected to be exceeded at a site with a probability of one per cent per annum.

The current risk levels in the NBCC are calculated by the method of extreme values as developed by Milne and Davenport (1969) and applied to the catalogue of Canadian earthquakes maintained by the Earth Physics Branch. In essence, the approach assumes that future earthquakes will reoccur with the same spatial and temporal distribution as in the past.

Recent studies by Knopoff and Kagan (1977) and Weichert and Milne (1979) have shown that despite the theoretical attraction of the extreme value method the results are not as stable as had been supposed, especially for regions where the seismic history is relatively short. An alternative approach developed by Cornell (1968) lessens this particular problem by explicitly enabling the seismologist to inject whatever tectonic information may be available. For this calculation, all available geological and geophysical information is used to partition the region about a site into zones of earthquake occurrence. Then a rate of earthquake occurrence, together with an estimate of the maximum earthquake expected is established for each zone.
The effects of the seismicity in each zone is assessed at the site, to develop an estimate of the level of seismic ground motion that is expected to be exceeded at a given probability. In delineating zones, the basic assumption is that earthquakes have a uniform probability of occurrence within each and that it is possible to specify the maximum magnitude earthquake that can occur. The method provides a measure of seismic risk with considerable areal smoothing and has the advantage of explicitly allowing the seismologist to perform a sensitivity analysis on the initial assumptions. Basham *et al.* (1979) have applied Cornell's method to Eastern Canada and show that the results are relatively insensitive to the initial assumptions at probabilities of 10^{-2} per annum, but by 10^{-3} per annum the effects of variations in the initial assumptions become apparent. They show that for more conservative estimates, i.e. for probabilities smaller than 10^{-3} per annum the results are

increasingly dependent upon the seismicity model used and hence the results become essentially deterministic rather than probabilistic.

For most applications, estimates of seismic risk in the range from 10^{-2} to 10^{-3} per annum are usually judged appropriate. Additional conservatism can of course be provided by multiplying these estimates by factors of assurance (safety factors) but, of course, the result is then deterministic.

The seismic history of North America is relatively short when compared to some of the other seismically active regions of the earth. The first entry in the Canadian catalogue cites a local Indian tradition to the effect that a major earthquake occurred between the two voyages of Jacques Cartier in 1534 and 1535 (Smith, 1962). Studies of the Chinese record which dates back to 1189 B.C. and the history of the Eastern Mediterranean and Middle East during the last seven centuries, show that seismicity is not always a stationary phenomenon even when averaged over periods comparable to the return period of the major earthquakes. It has been suggested by some that the rather dramatic shifts in seismicity seen in China and along the Anatolian Fault in Turkey may be peculiar to these regions where the tectonic style is one of interplate tectonics in a continental setting. In the intraplate environment of eastern North America it has been suggested that the seismicity is, in general, randomly distributed in more or less well-defined zones with localized regions of more intense activity such as Charlevoix, Charleston and New Madrid. While there is no question that these latter zones are well defined, the general concept poses important and, as yet, unanswered questions about such moderate earthquakes as those that occurred at Temiskaming in 1935 (M6.2) and Cornwall in 1944 (M5.9). Do these events identify localized, isolated zones where future significant earthquakes can be expected to reoccur, or are they representative of earthquakes that can be expected to occur with equal probability in other parts of the broad West Quebec zone of earthquake occurrence delineated by Basham *et al.* (1979)? Clearly, for risk purposes the two hypotheses have different consequences for sites in or near the zone. The latter hypothesis substantially increases the risk throughout the zone and does not differentiate Cornwall and Temiskaming from other towns in the zone, while the former hypothesis raises the risk near these two towns and depresses the risk elsewhere. Our present state of knowledge does not allow us to choose between the two. Hence we are forced to use judgement and to adopt the hypothesis that is most appropriate for the application in question. For example, if a critical engineering structure were to be sited near Temiskaming it would be natural to adopt the more conservative assumption that the 1935 event was typical of significant events that will occur there in the future.

The above discussion is most relevant for structures whose expected lifetime is measured in tens of years and is short, or at least less than the available history of seismicity. But some toxic waste disposal facilities, such as a nuclear waste repository, are anticipated to have a lifetime measured in thousands rather than tens of years. Here we are faced with the double problem of making highly conservative estimates of risk (exceedance estimates per annum) and of ensuring that these are relevant for very long periods of time. Such assessments will require, in addition to the studies outlined above, evidence from two further lines of research. The first, and most simply undertaken, would be to enhance the seismic monitoring capability of the currently installed National Seismograph Network, which is capable of detecting and locating all earthquakes of magnitude 3½ or greater anywhere in Canada. The threshold is lower than this in some more active regions but is not uniformly lower in the large region identified by the Federal and Ontario Governments as having potential for a nuclear waste repository. Enhanced monitoring capability will either provide further evidence that some parts of the region are indeed currently aseismic or alternatively that these parts do have seismic activity, albeit at very low levels. Very small earthquakes are not expected to pose a significant risk of themselves, but they would naturally be taken as evidence of the potential at very low probabilities for damaging events in the future.

The second necessary line of research is to attempt to find geological and geophysical evidence to support the delineation of the zones of earthquake occurrence as currently proposed by Basham *et al.* (1979). At present these are largely based on the available history of seismicity. Research at the Earth Physics Branch on the West Quebec Zone suggests that the careful comparison of topographic, lineament, magnetic, gravity and geological data with the seismicity reveals some weak correlations. Further work is required to establish the significance of these but the objective is clear: to improve our understanding of the processes that currently concentrate the seismicity of Eastern Canada into fairly well-defined, if broad, zones. Such an understanding would provide confidence that the relatively brief sample of seismicity now available is representative of future activity.

Risk of Induced Earthquakes

While the ambient seismic risk is most relevant for the static storage of wastes, the risk of induced earthquakes is probably of greater concern in the disposal of toxic wastes by fluid injection in the crust. Necessary conditions that must be satisfied if fluid injection is to result in the triggering of earthquakes are (McClain, 1970): (1) the presence of a regional tectonic stress field that is near to the breaking strength of the weakest section (e.g. pre-existing faults) in the region before fluid injection, (2) the reservoir formation accepts waste fluids into its pore space (e.g. along a fault) but its permeability is low enough to enable pore pressure to build up, (3) the rate and volume of fluid injected is great enough to increase significantly the formation pressure over a wide area.

Induced seismicity due to reservoir filling is also thought to be controlled by the above conditions. The only significant difference is that the fluid percolation rate is much slower as the incremental fluid pressure is limited to the hydrostatic pressure in the reservoir.

There are now several documented examples of induced seismic activity in North America. One of the best known is the long series of earthquakes that began with high-pressure fluid injection into a deep well at the Rocky Mountain Arsenal near Denver, Colorado. Evans (1966) reports a strong correlation between the frequency of these earthquakes and the volume of fluid injected into the Precambrian crystalline basement rocks underlying more than three kilometres of sedimentary rocks. To explain this sequence of events Healy *et al.* (1968) applied the theory of Hubbert and Rubey (1959) in conjunction with a knowledge of the geology and tectonics of this relatively aseismic region. They postulated that the injected fluid percolating along a nearby major unhealed fault resulted in an increase of about 25 per cent in the pore pressure around it. This reduced the frictional resistance of the fault to the point that the ambient tectonic stress field caused a sudden slippage to occur. Similarly at Rangely, Colorado, fluid injection for the secondary recovery of oil in the sandstone triggered a series of earthquakes along another nearby pre-existing fault. Earthquakes were not induced in this case until the fluid pressure exceeded the original pore pressure by about 50 per cent. The theory of Hubbert and Rubey, together with the Coulomb-Mohr theory of shear failure were again able to account for this man-made seismic activity.

In Canada there are documented cases of a spatial correlation between seismic activity in zones of low seismic risk and fluid injection; however, no definitive temporal correlation has been found such as that reported at Denver and Rangely. There is a spatial correlation between the Snipe Lake earthquake (M5) in north-central Alberta in 1970 and fluid injection (Milne, 1970), but this earthquake occurred while no unusual change was observed in the rate of fluid injection in the epicentral region. In southern Saskatchewan Horner and Hasegawa (1978) have noted a spatial correlation between the sparse seismic activity, areas of oilfield and potash brine injection and possible basement zones of weakness. In some localities the rate, pressure and volume of fluid injection are comparable to those at Denver and Rangely, but the absence of intense swarm activity such as observed in Colorado implies the absence of sufficiently large zones of weakness. Although the data are sparse, the hydrofracturing experiments of Haimson (1977) do not indicate any significant regional differences in the tectonic stress field at shallow depths in the central United States. Some of the sporadic seismic activity in the area may be due to physical and chemical changes in the rocks (cf. Kisslinger, 1976) in the presence of fluids, or to natural or industrial salt solution processes. Until more accurate estimates of the focal depths of southern Saskatchewan earthquakes are available, the question of whether these earthquakes are due to natural tectonic processes or to fluid injection is difficult to resolve.

In the foothills of the Rocky Mountains near Rocky Mountain House, Alberta, some spatial and temporal correlation has been observed between oil production rates and earthquake swarm activity (R. J. Wetmiller, pers. commun. 1979). No fluid injection schemes comparable to the Denver or Rangely examples are in operation near the Rocky Mountain House earthquakes, but many such schemes do exist in other areas of Alberta and are not connected with known seismic activity.

Other Stress-Related Risks

For a nuclear waste repository there are other stress-related risks that must be assessed for proper engineering design. Mining experience in the Precambrian Shield of northern Ontario and Quebec has shown that the mining process itself can produce local concentrations of stress that sometimes lead to rock bursts and other related phenomena (Hodgson, 1958). Cook (1976) has reviewed the evidence and concludes that regional tectonic stresses and local zones of weakness are again of critical importance.

A further problem associated with nuclear wastes is the considerable heat that must be allowed to dissipate. A large increase in temperature about the storage cavern will undoubtedly induce further stresses. The risk inherent in these activities is that the sum of the tectonic and induced stresses may exceed a critical value and lead to rock failure. A careful modelling and monitoring program can ensure that the incremental stresses are kept to safe levels.

Engineering Application

In the above, we have discussed the considerations that seismologists apply in arriving at estimates of seismic risk. However, earthquake engineers base their design upon either response spectra or vibratory ground-motion time-histories. The former provides information on the base shear stress, kinetic energy and strain that the structure must withstand while the latter is important in assessing structural fatigue.

The choice of the appropriate levels of response spectra and time histories depends upon a number of site specific factors. Some of these are: the effect of the local geology on the incoming seismic signals; the depth of burial of the structure; the nature of the seismicity that affects the site; and the rock-structure interaction.

There is as yet little experimental data available on the manner in which seismic ground motion attenuates with depth from the surface. Iwasaki *et al.* (1977) present some recorded data from Japan that suggest that the attenuation can be appreciable but also show other data that suggest the opposite effect. Clearly the data are heavily dependent upon the local geology, the focal depth, location and the source mechanism of the earthquake in question. It would appear that there is as yet too little data to generalize, and more work is required. Fortunately a number of countries are now installing vertical arrays of strong motion instruments and significant data on this problem can be expected in the near future.

Conclusion

In this discussion, we have touched lightly upon the available techniques and some of the problems associated with assessing the seismic risk at the site of a waste disposal facility. For nuclear waste disposal repositories, the risk comes mainly from the ambient or natural seismicity. The induced seismicity associated with the mining process and thermally induced stresses are of secondary concern. For waste disposal by fluid injection the risk is primarily associated with the possibility of triggering earthquakes by the fluid injection process itself.

We do not believe that the seismic risk associated with toxic waste disposal will prove to be an insuperable problem. We do insist however that it should be considered most carefully in order that appropriate engineering measures may be taken to mitigate the associated potential hazards to acceptable levels.

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