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NORTHWEST EUROPEAN SEISMIC HAZARD: THE SEARCH FOR A REGIONAL PERSPECTIVE

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ABSTRACT

Compared with the politically more homogeneous continental USA, the practice of seismic hazard assessment in Northwest Europe is highly fragmented, varying widely according to national tradition, and depending on the individual preference of the hazard analysts in each country. This fragmentation is deleterious in so far as a broad regional perspective is required in understanding the physical characteristics of seismicity in neighbouring countries. A discussion is presented here of some of the principal issues in seismic hazard assessment on which progress might be advanced significantly, if there were greater international scientific cooperation across the borders of Northwest Europe.

KEYWORDS

Northwest Europe; hazard methodology; kernel estimation

INTRODUCTION

Whatever political and economic measures may be under way to promote European unity, it is as a collection of individual nation states that most activities are still pursued, not least the evaluation of seismic hazard. Methodologies for assessing seismic hazard do differ quite significantly within Europe, as do the quality of seismological and geological databases, and the breadth of seismotectonic research. Furthermore, the geography of earthquake catalogues is inextricably intertwined with political geography. A number of European initiatives have been taken to tackle some of the seismological problems arising from the political fragmentation of the continent; reconciliation of earthquake catalogues, construction of seismotectonic maps etc., but the implications for the process of seismic hazard evaluation remain to be fully explored. It is the purpose of this paper to raise some of the issues in Northwest European seismic hazard assessment which have an international dimension, and cannot adequately be resolved on a national level.

MAGNITUDE VERSUS INTENSITY AS A HAZARD MEASURE

A common aspect of the cultural heritage of Northwest Europe is a long historical record of earthquakes, extending back many centuries before the advent of instrumental recording. Compilation and interpretation of macroseismic information lead naturally to the assignment of Intensities, and the production of Isoseismal maps. A catalogue of peak Intensity values can be used directly for deterministic assignment of ground motion, with minimal requirement for numerical processing. In continental Europe, the direct use of Intensity data is quite common, as is the adoption of a deterministic seismic hazard methodology. Alternatively, the Intensity data could be used as a basis for calculating Intensity recurrence relations, which then form the basis for a probabilistic computation of Intensity hazard.

Offshore events have ill-defined epicentral Intensities, but their felt radii may be reasonably well contrained. For countries such as Britain and Norway, which have long coastlines and notable levels of offshore activity, felt radii, rather than peak Intensity, underpin the preferred seismic hazard methodology, which is probabilistic in approach. Correlations have been developed between felt radii and magnitude, using 20th century instrumental data, and these have been applied to estimating magnitudes for historical events. These correlations allow the integration of macroseismic and instrumental data within a single joint catalogue, which is central to a magnitude-based probabilistic hazard assessment. To the extent that fault slip rate can be converted into seismic moment release rate, and magnitude recurrence, a magnitude-based methodology can readily incorporate geological data on local faulting, which is often a contentious issue in probabilistic site-specific hazard assessment.

ACTIVE FAULTING IN A LOW SEISMICITY ENVIRONMENT

The fundamental geodynamic issue concerning Northwest European seismotectonics is the extent of dynamical interaction within this section of the Eurasian Plate, which results in the coupling of regional seismicity. The historical record of earthquakes in Northwest Europe extends back a millenium, and establishes this region as being of low seismicity. As documented in the historical record, Northwest Europe has experienced a few tens of magnitude 5 M_s earthquakes, but only a relatively small number of magnitude 6 M_s earthquakes. For this period, the seismic energy release rate for Northwest Europe has been very low compared with plate boundary regions of the world; but it may have switched from higher levels in preceding millenia.

The need for a broad Northwest European perspective is needed when considering important issues in engineering seismology such as Maximum Magnitude and the active status of on-site faults. A local or even national viewpoint is too restrictive and parochial. The concept of Maximum Magnitude can only be given a seismotectonic interpretation within an international European context. Estimates of Maximum Magnitude based on individual fault size and displacement in earlier tectonic regimes may well not be relevant to the current tectonic regime. In Britain, for example, it is not uncommon for site investigations to reveal the presence of local faulting, which may cause concern over possible ground rupture. Even without any convincing neotectonic evidence, questions may be raised as to the activity rate associating with the faulting, and the corresponding Maximum Magnitude. In assessing the likelihood that an on-site fault may generate a magnitude 6 earthquake in the next several decades, the current regional seismotectonic context has to be considered.

If a magnitude 6 earthquake were to occur in Northwest Europe, it would occur within the population of candidate faults. A magnitude 6 earthquake is associated with a comparatively small rupture area of the order of 100 sq.kms. The number of faults in Northwest Europe capable of generating a magnitude 6 earthquake, (which is the size of the candidate population), may well be many hundred. The likelihood of any specific fault generating a magnitude 6 event in North West Europe will vary according to its recent tectonic history, associated seismicity, etc.. There is thus a taxonomy of North West European faults, with a ranking based on current activity rate. Whatever current activity rates are assigned to individual faults within this taxonomy, there is an overall consistency criterion within the existing seismicity state, which is reflected in the limited level of seismic energy released over the past thousand years.

The need to appreciate the size of the population of candidate faults is essential if a sound and unbiased probability is to be assigned to the activity of an on-site fault. It is all too easy to perpetrate a probabilistic fallacy, if the candidate fault population is ignored in evaluating the significance of the evidence presented by any individual fault. In this regard, salutary lessons may be learned from the use of statistics in forensic criminal investigations. Eggleston (1983) has coined the so-called 'island' problem, which generalizes this situation. On this hypothetical island, a crime is committed, and the suspects are the island population. If the criminal is known to have some trait, then the likelihood that a suspect having this trait is the criminal is weighted inversely by the number of suspects having this trait. The key lesson is that, however incriminating a trait or piece of evidence may be, the importance of this evidence cannot be properly weighed until a general survey has been undertaken of the frequency of this trait. It is easy to jump prematurely to conclusions based only on scrutiny of a single piece of evidence, without taking account of the wider context.

In evaluating the seismic hazard for an engineering facility over the next several decades, the regional dynamical constraints on the assignment of activity rate to an on-site fault need to be recognized. (For a storage facility with a lifetime many times as great, numerous events can occur and the regional constraints become correspondingly weak). The neglect of regional implications for local fault activity stems logistically from the site-specific nature of the data gathering process, which tends to create a marked disparity in the quality and quantity of fault-specific information within a region; faults in areas lacking sites of engineering concern are often poorly charted.

For a fault on the site of a critical installation, conservatism may require an estimate of current fault activity rate to be based on a geological average over many millenia. However, this does not accommodate the cumulative evidence from regional faults, nor does it make allowance for non-stationarity. In evaluating the likelihood that the on-site fault might generate a magnitude 6 earthquake within the next several decades, (e.g. for analysis of the fault rupture hazard), it is necessary to estimate the size of the population of regional faults capable of generating such events. This would require the use of data acquired from other site studies, as well as from general national and European investigations. Beyond the resources of available data, inferences may have to be based on current fractal models of fault density and size. Appeal to such arguments may be innovative in the context of seismic hazard assessment, but then so also would be the imposition of exclusionary site criteria based on the ubiquitous Tertiary faulting in Northwest Europe.

ZONATION IN A LOW SEISMICITY ENVIRONMENT

Given the national horizons which tend to limit the perspective of seismic hazard analysts in Europe, it is unfortunate, if not surprising, that a degree of political correctness pervades the delineation of boundaries of seismic zones. Thus zones may conveniently be bordered by coastlines or land frontiers, which have no current seismotectonic significance. A recent zonation for Holland has this feature. Zones may be extended tentatively into neighbouring countries, but with diminishing scientific confidence and conviction. Remembering that within a country there may be major differences of opinion on zonation, European consensus on zonation remains a distant and elusive goal.

An apposite example of an area of Northwest Europe where an international border marks an abrupt transition in seismic hazard assessment practice is the Strait of Dover, at the eastern end of the English Channel. Apart from the Channel Tunnel which now links Britain and France, there are a number of critical industrial installations occupying strategic coastal sites on either side of the Strait of Dover, both in Kent and the Pas de Calais. Among these are nuclear power plants and LNG storage tanks. A proper seismotectonic synthesis for a site on one side of the Strait must inevitably involve the other. Given the ambiguities in comprehending the tectonics of this low seismicity region, it is not surprising that seismotectonic opinions have been divided, and that different syntheses have been developed by geologists working independently in Britain and France.

Seismotectonically, France is ambivalently situated partly in northern Europe, and partly in southern Europe. In the more seismic regions, such as western Provence (Combes, 1984), the quantity of evidence for correlating seismicity with active seismogenic structures is sufficiently strong as to support a deterministic approach to national seismic hazard assessment. This deterministic approach is based on a procedure which involves partitioning the region around the site into distinct seismotectonic zones. The historical peak Intensity within each zone is then postulated to occur, within the zone, at the most conservative location with respect to the site. The highest resulting Intensity is then calculated, allowing for the attenuation of Intensity with distance from source to site.

For a site on the Northeast coast of France, a basic problem exists in defining a regional seismotectonic zone. Should it extend northwards to include the Dover Straits earthquake of 1580/4/6, which caused damage in both England and France? Perhaps the zone should extend further northwards into East Anglia so as to include also the Colchester earthquake of 1884/4/22, which, in a few villages, caused some of the worst damage of any British event? Neither extended zone geometry would be recognized by British seismologists as conforming to the observed spatial pattern of seismicity.

If these two major events are to be grouped in the same zone as the site, then there is some sensitivity to the assignment of their peak Intensities: VII - VIII. The peak Intensity for the 1884 event is quite well constrained, but, since the epicentre of the 1580 earthquake was almost certainly offshore, the peak Intensity for this event is inevitably speculative. Given the qualitative nature of Intensity as a measure of ground motion, the associated ground motions accompanying a peak Intensity of VII - VIII are also somewhat speculative. The ground motions of the shallow 1884 event and the deeper 1580 event would have been markedly different, even if the peak Intensities might have been similar.

Procedures have been developed in France to estimate Intensity-dependent seismic response spectra via statistical analysis of strong-motion data. With the continuous enlargement of the global strong-motion database, revisions are regularly undertaken. The most recent review of this compendious work has been undertaken by G. Mohammadioun and presented at the 10th European Conference on Earthquake Engineering in Vienna (1994). Intensity-normalized spectra have been long favoured in France, but have not found application across the English Channel, where preference has been given to the construction of magnitude and distance-dependent spectral attenuation relations which are needed for the generation of U.K. uniform hazard spectra. The mathematical correspondence between site-dependent Intensity-normalized spectra and site-specific probabilistic uniform risk spectra has recently been established within the framework of a bilateral Anglo-French earthquake engineering initiative.

SPATIAL SCALES OF SEISMIC ZONATION

The fundamental difficulty with defining seismic zones in areas of low seismicity is that often the correlation between seismicity and geological structure is too poor for reliance to be placed on geological controls. The spatial pattern of seismicity, sparse though it may be, then provides the major data resource for seismic zonation. In analysing the spatial pattern, various basic dynamical principles need to be borne in mind, not least the significance of the magnitude-frequency statistics. The Gutenberg-Richter magnitude-frequency relation is so familiar to seismologists, that a power-law for the release of seismic energy is not the surprise it might appear to a statistical physicist first introduced to earthquake phenomenology. Power-laws are a manifestation of scale invariance, indicative of the capability of earthquake generating systems to self-organize to a critical state with no characteristic length scale other than the size of the system. (Bak, Tang and Wiesenfeld, 1988). Such systems are far from equilibrium, being driven by the input of energy which is stored and then dissipated in earthquake activity. Over a long period of geological time, the lithosphere has evolved to a steady-state where the build-up of stress is balanced by the release of stress during earthquakes.

Given the fundamental physical significance of the magnitude-frequency power-law, its status within probabilistic seismic hazard assessment deserves to be re-evaluated. In particular, the implications for zonation need to be addressed. For logistical reasons, it is usually the case that, only after seismic zones have been delineated on geological and seismological grounds, is an attempt made to estimate zonal magnitude-frequency relations. Exploratory studies of magnitude-frequency statistics prior to zonation are not routinely undertaken as an aid to dynamical understanding. If a substantial weight has been accorded to geological knowledge, relative to seismological information, zonal magnitude-frequency relations may indeed be poorly constrained. This may be adequate if such power-law relations signify nothing more than convenient formulae by which activity rates may be computed, but this approach fails to appreciate the uniqueness of the power-law itself. Within contemporary methods for seismic area source modelling, little would change if the magnitude-frequency relation were not a power-law, i.e. if earthquake occurrence were not a self-organized critical phenomenon. The mathematical formula for deriving zonal recurrence relations would be different, but the actual zonation would not be altered, still less the underlying principles of zonation.

With the scale-invariant power-law dictating earthquake occurrence, long-range interactions typical of many critical phenomena can take place, which means that small perturbations can trigger earthquakes at a distance (Anderson et al, 1994). This arises dynamically through the complex interaction of faults, rather than the direct transmission of stress (Turcotte, 1992). The possibility of long-range correlations of seismic activity may limit the scope of partitioning a region into zones of independent seismicity. Across the boundaries of such zones, there is no mechanism by which earthquakes can migrate or be triggered.

The language of probability is well suited to describing seismogenic processes, as with many other complex dynamical systems, because of the erosion of deterministic predictability (Turcotte, 1992). For quite different reasons connected with the practice of engineering risk evaluation, probability happens also to be the primary language of contemporary seismic hazard assessment. This duality in mathematical formalism should be manifest in a dynamical approach to the modelling of seismic area sources, which recognizes that recurrent earthquake epicentres are not deterministically transfixed, but are liable to migrate or be perturbed by cooperative fault interactions, in a magnitude-dependent manner. Allowing for such dynamical variations, each earthquake can be considered to be an automodel of a sequence of earthquakes (Knopoff and Kagan, 1980), which constitutes a multiple realization of the basic stochastic crustal process.

Venturing beyond the restrictions of zonation, the general functional representation of mean activity rate is $\lambda(M, \mathbf{x})$, which is the expected annual number of events of magnitude M occurring at location $\mathbf{x}$. The assignment of $\lambda(M, \mathbf{x})$ may be based partly on geological grounds, and partly on seismological data. The simplest assumption is to take $\lambda(M, \mathbf{x})$ to be non-zero only at the epicentres of historical earthquakes of magnitude M. However, the principal weakness of methods such as this which are based directly on the historical catalogue (e.g. Milne and Davenport, 1969), is that they fail to take account of the fundamental dynamical variability in the location of an event.

To remedy this deficiency, $\lambda(M, \mathbf{x})$ can be estimated via a statistical smoothing operation, which recognizes the fundamental probabilistic nature of the discrete sample of historical observations. The smoothing operation involves the introduction of a kernel $K(M,\mathbf{x})$, which is a magnitude-dependent multivariate probability density function (Woo, 1995). Various forms of kernel $K(M, \mathbf{x})$ might be chosen. An exponential form yields a rapid decay. Another example suggested by Vere-Jones (1992) is the following infinite-range power-law decay, dependent on the radial separation distance $r(M)$, a fall-off parameter a and a magnitude-dependent bandwidth parameter $h(M)$:

$$K(M, \mathbf{x}) = [\,(a-1)/\pi\,]\; h(M)^{-2}\,(1 + r^2/h(M)^2)^{-a} \qquad (1)$$

According to Vere-Jones (1992), a typical value of a is between 1.5 and 2, which yields a cubic or quartic fall-off of probability density with epicentral distance. This expression is isotropic, but a dependence on orientation can be readily included to represent an alignment of seismicity along a particular axis. In actual implemention, the parametric form of kernel tends to be less important than the bandwidth.

For a dissipative system displaying power-law behaviour, the probability of an avalanche-type event occurring within a given spatial extent should scale with the event size (Kadanoff, 1990). The kernel bandwidth h(M) should therefore scale according to earthquake size, which might be taken in the present context to be fault length L. Given the standard form of logarithmic correlation of fault length L with magnitude M, h(M) can be parameterized as $h(M) = H \cdot \exp(kM)$, where H and k are constants which are region-specific, and may be estimated from an analysis of the spatial clustering of earthquakes of varying magnitude. By analysing average nearest-neighbour distances for events of similar magnitude, an approximate connection between the bandwidth scaling factor k and regional b-value may be found.

Although problematic within the context of area zonation, magnitude-dependence of the spatial distribution of earthquakes is automatically represented within the kernel estimation methodology, through bandwidth scaling with fault size. Through this kind of magnitude scaling of the bandwidth, it is possible to replicate many pathological spatial patterns of intraplate seismicity, which do not conform to the plate boundary archetype of events of all magnitudes packed into a confined fault zone. In particular, it is possible to simulate some perplexing intraplate scenarios where damaging magnitude 5 or 6 events occur unexpectedly in regions of low ambient seismicity, where moderate magnitude events are historically rare.

Within the context of Northwest Europe, an illustrative example is provided by the North Sea earthquake of 1931/6/7, which was instrumentally measured as having 5.5 M_s, and therefore is the largest earthquake in the region of the British Isles. At the time of its occurrence, this event was a major surprise, given the lack of an event of such size and in such a location in the historical record. A broad bandwidth of several hundred kilometres would be consistent with the high magnitude, and also with the fact that this event sets a crucial uppermost reference point in the Gutenberg-Richter magnitude-frequency relation for the British Isles as a whole. Thus from a dynamical viewpoint, this event is one which should not be confined to a narrow zone, but should be free to migrate over a large distance. Within the context of Euclidean zonation, this could only be realized if much of Britain were subsumed within a single homogeneous zone; which would be discordant with clear geographical variations in the distribution of lesser magnitude events.

CONCLUSIONS

Were it not for political boundaries which divide Northwest Europe, the perception of the characteristics of seismicity in this region would be somewhat different. Although expedient for seismic hazard analysts to concentrate their efforts on their own countries, the regional perspective is easily obscured. The dynamical coupling of faulting within the territories of Northwest Europe suggests some degree of interaction in the seismicity of sub-regions, which may be manifest in spatial-temporal fluctuations in activity. Overall in Northwest Europe, the low level of seismic energy release over the past millenium serves to constrain the collective rate of activity of faults in the region. Thus, the assignment of activity rate to a particular fault should not be based only on local geological evidence, but involve a reference to the total regional population of active faults. Appreciation of the behaviour of the ensemble of Northwest European active faults should help seismologists to be prepared better for a damaging earthquake arising apparently from nowhere.

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