EARTHQUAKE ENGINEERING IN REGIONS OF LOW SEISMICITY

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SUMMARY

Seismic risk in regions of low seismicity is evaluated using the UK as an example. This involves quantifying the seismic hazard and also the vulnerability functions for a range of typical structures. Predictions are made as to the effects of a range of specific earthquakes occurring under two existing areas of the UK. By integrating the hazard and vulnerability seismic risk has been calculated in terms of cost and fatalities and compared to those arising from other types of hazard. Recommendations are made as to when, and in what form, seismic considerations may be necessary.

INTRODUCTION

In most parts of the world in regions of low seismicity the codes of practice do not require any consideration of earthquake loading in the design of conventional structures. This is the case in the UK and for the last two centuries, during which there has been a high standard of historical recording, the quantity of damage caused by earthquakes has been low. The greatest damage occurred in the 1884 Colchester earthquake where several houses were partially destroyed accompanied by considerable public alarm. In the same period about 40 earthquakes have caused minor damage, for example to chimneys. Very few casualties have been experienced with not more than 8 deaths being recorded since 1580 [20].

Until now structural design in the UK has only acknowledged earthquake loading for nuclear plants and other facilities having a high consequence of failure. The issue of earthquake design criteria for conventional structures has arisen in the UK because of the proposal for a standard European seismic code. Not surprisingly, the prospect of earthquake design rules for conventional structures in the UK, with much lower seismicity than Italy or Greece, has been greeted with concern and alarm by local designers and building regulators. Nevertheless the 1989 Newcastle, Australia earthquake showed significant weaknesses in conventional structures and highlighted the possibility that, even in areas of low seismicity, some minimum design requirements may be necessary.

To enable these issues to be explored the UK Government, through the Department of the Environment, commissioned a preliminary study of UK seismic hazard and risk. This project has been carried out mainly by Ove Arup and Partners in London. Contributions to the work have been made by Delta Pi Associates, Athens who assisted with seismological aspects and methodology and Cambridge Architectural Research, who supplied the database of damage to conventional structures and methods for applying this. In addition Earthquake Documentation and Research, Cambridge assisted with verifying the historical earthquake record and Geomatrix, San Francisco supplied methods developed for seismic hazard assessment of the eastern USA. The views expressed here are those of the author and do not necessarily reflect those of the Department of the Environment.

The objectives of the study were to:

i) develop an appreciation of seismic risk to the UK in terms of how it affects the built environment as a whole and
ii) determine whether seismicity should be taken into account in future planning decisions and, if so, how.

The following definitions were adopted:

<u>Seismic Hazard</u>: The level of ground motion due to seismic activity at any particular location which may arise due to a specific earthquake or which may be expected at a prescribed rate of occurrence.

<u>Seismic Vulnerability</u>: The damage level to a specific structure arising from a given level of ground motion.

<u>Seismic Risk</u>: The level of damage due to a specific earthquake or which may be expected at a prescribed rate of occurrence.

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Methodology of The Study

Quantifying the level of seismic activity in the UK. The available data on instrumental and historical earthquakes as well as the tectonic evolution of NW Europe and the British Isles has been studied and assessed in terms of geographical distribution of seismic activity.

Calculating the level of seismic hazard in the UK. By combining the seismic activity rate with an attenuation relationship which relates ground motion to earthquake magnitude and distance from the source, the expected level of ground motion at any rate of occurrence can be calculated. Various hazard parameters have been used including intensity and response spectra. The average seismic hazard level and the possible variation of hazard around the UK has been estimated. These have been derived for sites underlain by bedrock from the surface. Since local soil conditions can have a significant effect on the earthquake ground motion their effects have also been considered.

Establishing vulnerability functions of various types of structures. By examining observed damage data for common types of structures various vulnerability functions have been established. These are expressed as the fraction of the building stock that will experience at least a given level of damage for a particular value of ground motion. A simplified analysis has been used to check these functions for reinforced concrete structures.

Microzoning Studies. Two areas in the UK were selected and their risk to a range of specific earthquakes has been assessed. Each area is about 400 km^2 and contains a broad cross section of building stock, soil types, land forms, etc. Predictions were made for the total cost, the number of structures that would experience various levels of damage and for the number of fatalities.

Calculating the annual risk from seismic activity. By integrating the seismic hazard with the vulnerability functions annual risk has been determined. Sensitivity studies were carried out to determine the relative importance of the various uncertainties in the hazard and vulnerability.

Comparison of Earthquake risk to other risks. The study has enabled an estimation of the annual cost of earthquakes to be made. This is the average cost over a very long time and consequently includes the effects of very unlikely large earthquakes which may give rise to very large costs. Therefore the average cost actually experienced over a time period even as long as 100 years may be very different from the estimate. Nevertheless, to be able to place seismic risk in context, the estimated seismic cost and number of fatalities were compared with those observed in the UK from other hazards such as weather, fire and subsidence.

SEISMIC ACTIVITY IN THE UK

The following section describes the published recent instrumental and macroseismic data available for UK earthquakes.

Recent Instrumental Data on UK Earthquakes (1980-1990)

Up until the early 1960's, seismological monitoring in the UK was limited to a few non-standard instruments. The commencement of worldwide monitoring of nuclear tests in the mid 1960's provided a new impetus to seismic monitoring in the UK. The Institute of Geological Sciences, now the British Geological Survey (BGS), installed several instruments near Edinburgh. This network was expanded and by 1979 the instrumental coverage, was such that Richter local magnitude (M_L) 2.5 could be detected anywhere within the UK [6]. From the BGS records the distribution of epicentres of earthquakes, $M_L \geq 2.0$, recorded since 1980, is shown in Figure 1. A major earthquake which occurred during this period was the 1990, Bishop's Castle earthquakes in Mid Wales which had a magnitude M_L of 5.1 and caused some damage to chimneys etc.

Macroseismic Data (1200-1990)

The instrumental data available for the UK covers an extremely short time span when compared with the geological time scale involved in the recurrence of large destructive intraplate earthquakes. In order to extend the period of instrumental coverage of UK earthquakes a Historical Earthquake Catalogue was collated. This catalogue is for earthquakes of surface wave magnitude M_s greater than 4 and was derived from previous studies carried out principally for the nuclear industry. The studies included those by Principia Mechanica Ltd. and Soil Mechanics Ltd. in 1982, Ambraseys [2], various studies by Melville, reports by the BGS and the site specific studies for nuclear power plants. Most of the above sources included isoseismal maps (based on MSK Intensity). The magnitudes of most UK earthquakes that have occurred between 1700 and 1900 have been assessed using correlations between surface wave magnitude, M_s, and "felt" areas by Ambraseys [2].

Two data subsets of the Historical Earthquake Catalogue are considered to be complete over the whole of the UK (see Figure 2):

$M_s \geq 5.0$, over the period 1200 to 1990. A magnitude 5 earthquake should have been detected anywhere in the UK over this time period.

$M_s \geq 4.0$, over the period 1800 to 1990. The completeness of macroseismic data is influenced by factors such as availability of documentation and population density. Melville [18] drew attention to the fact that the most relevant documentary innovation after 1700 was the introduction of regular newspapers in London and the provinces. He concluded that for events with a felt area of approximately 10,000 km^2 (about M_s of 4), the catalogue is complete for England and Wales from 1750, and for Scotland from around 1800.

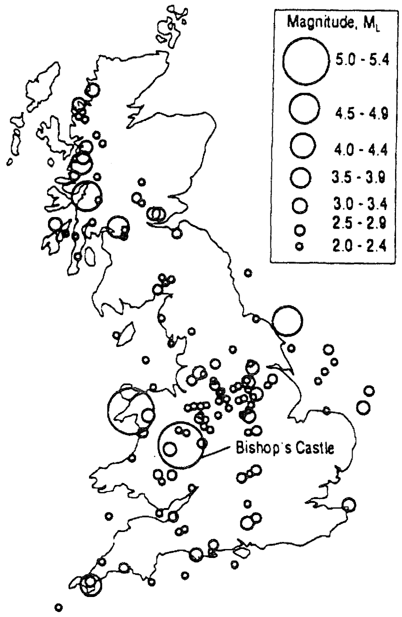

FIGURE 1 INSTRUMENTALLY RECORDED EARTHQUAKES 1980 - 1991

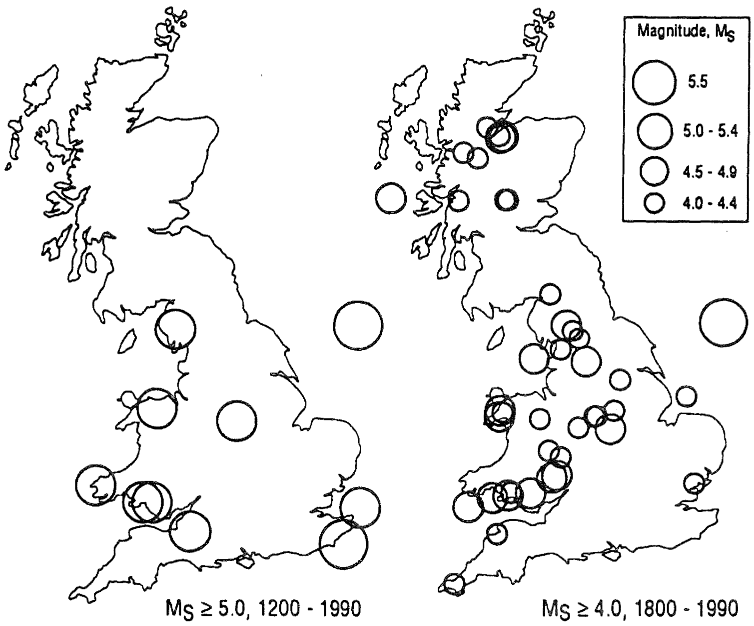

FIGURE 2 HISTORICALLY RECORDED EARTHQUAKES

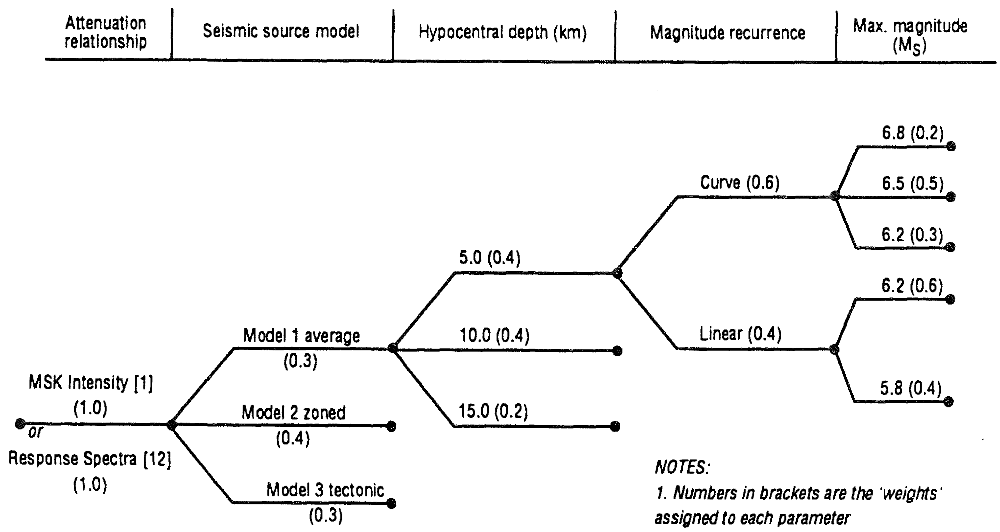

FIGURE 3 'LOGIC TREE' STRUCTURE FOR UK SEISMIC HAZARD ASSESSMENT

SEISMIC HAZARD ASSESSMENT

The seismic hazard assessment is necessary to determine the rate at which various levels of the ground motion will occur. For the purposes of the study the ground motion hazard was derived in terms of MSK Intensity and response spectra for a site underlain by bedrock.

When known active fault segments are known to generate earthquakes of similar size a deterministic method can be used for seismic hazard assessment. For intraplate regions such as the UK, this is not the case and a probabilistic method is required. Probabilistic seismic hazard assessments (PSHA) combine the seismic source zoning, earthquake recurrence and the attenuation relationships to produce "hazard curves" in terms of the level of ground motion hazard and annual frequency of being exceeded [11]. PSHA's have the distinct advantage that uncertainty in the input parameters (source models, attenuation relationships) can be incorporated explicitly using the "logic tree" method [9]. The "logic tree" structure developed for the UK is shown in Figure 3 and involves specifying discrete alternatives for parameter values and the relative likelihood, by way of weightings, that each discrete alternative is the correct value of the input parameter.

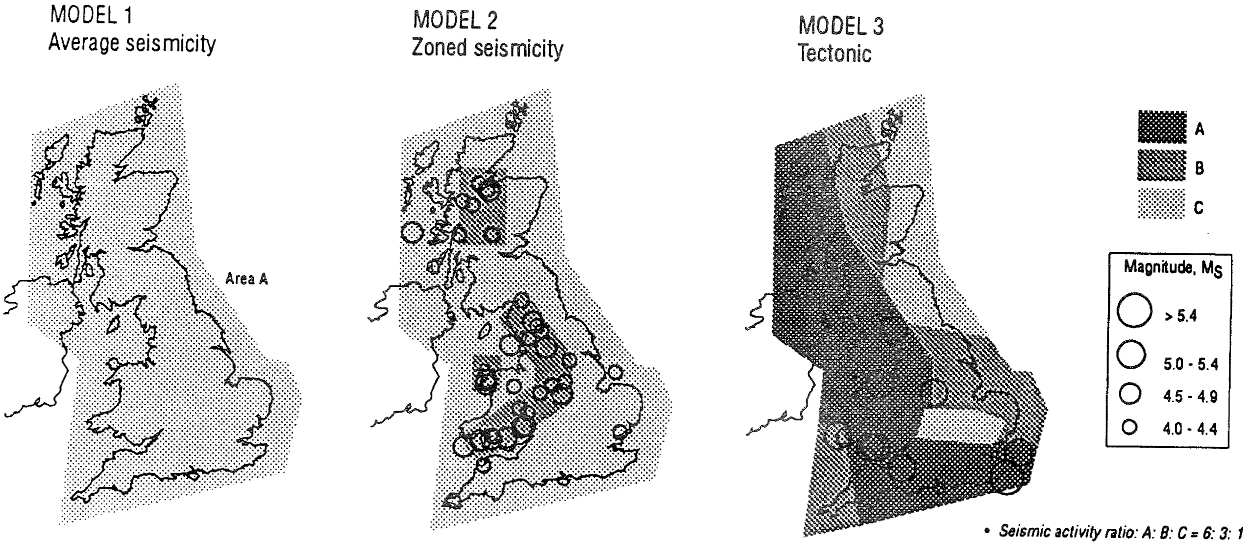

FIGURE 4 SEISMIC SOURCE MODELS

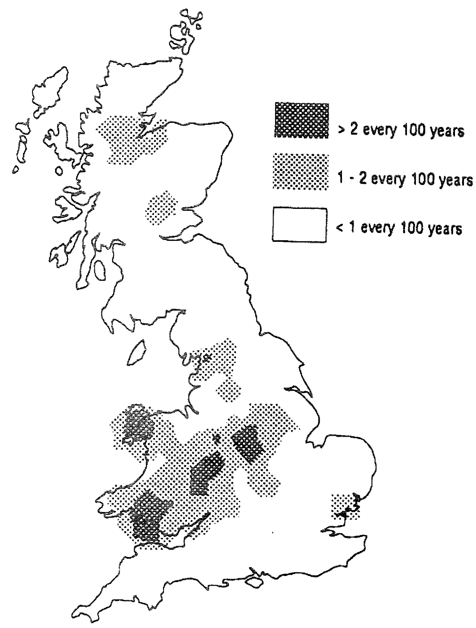

FIGURE 5 MSK INTENSITY RECURRENCE 1800 - 1991

Seismic Source Models

A major uncertainty in seismic hazard analysis within stable continental regions, such a the UK, is the delineation of the boundaries of seismic sources. In an attempt to allow for this uncertainty, three alternative seismic source models have been used as shown in Figure 4. The total energy budget was kept the same for all three source models within the whole area A.

The three models are:

Model 1: Uniform Seismicity

Model 2: Zoned seismicity. This model consists of three zones of higher activity. Similar seismic activity in terms of number of earthquakes per unit area was assumed in these zones and a lower background activity was assigned to the surrounding area. It is primarily based on the locations of earthquakes, $M_s \geq 4.0$, that have occurred in the period 1800-1900. The observed intensity recurrence, shown in Figure 5 and derived from isoseismal maps for the period 1800-1900, have also been used.

Model 3: Tectonic. This source model was based on deformation phases over the past 50 million years [19] and the activity of the tectonic zones was defined from the seismological record ($M \geq 5$).

For all source models the range of hypocentral depths shown in Figure 3 have been assumed. These were mainly based on macroseismic determinations.

Earthquake Recurrence

Figure 6 shows earthquake recurrence in terms of magnitude based on the historical and recent instrumental earthquake data described previously. Aftershocks and swarms have been deleted. Earthquake magnitudes for the historical events are plotted in terms of the M_s, whereas the recent instrumental data is given in terms of M_L. At magnitude 5 the M_L scale is broadly similar to the M_s scale [3]. The surface wave magnitude scale has been chosen for these hazard calculations as it is consistent with the adopted ground motion attenuation relationships.

Two basic recurrence relations were adopted, one being linear and the other curved. Both are limited by a range of maximum magnitudes as indicated in Figure 3. Various methods have been used to assess these maximum magnitudes including the EPRI worldwide intraplate regions data base [10]. A minimum magnitude, $M_s = 4$, has been used in the hazard calculations because the historical

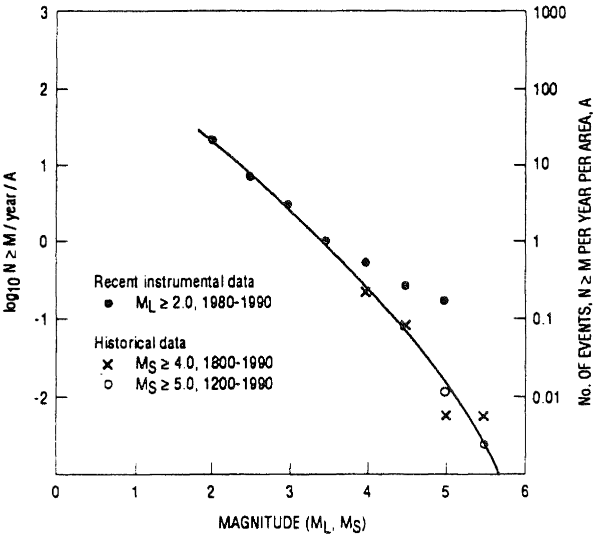

FIGURE 6 EARTHQUAKE RECURRENCE IN THE UK

record shows that the likelihood of an earthquake with a smaller magnitude causing any more than trivial damage is extremely low.

Attenuation Relationships

Attenuation relationships have been chosen for two hazard parameters:-

MSK Intensity. The MSK Intensity attenuation relationship developed for north west Europe [1] has been used. This macroseismic attenuation is based on isoseismals that envelope, rather than average observations. To obtain a "mean" relationship, the attenuation has been lowered by one half of an intensity unit. Variability in the attenuation relationship has not been published but for the study a standard deviation of MSK Intensity of 1.0 was assumed. This intensity attenuation relationship has been derived from data covering all types of soil conditions. It therefore incorporates the 'average ' effect of local soil amplifications.

Horizontal response spectra. The attenuation relationship recently derived for intraplate areas [12] has been used. The response spectral values are for a structural damping level of 5% of critical.

Seismic Hazard Levels

As stated above seismic hazard has been calculated for two parameters as follows.

MSK Intensity
A typical hazard frequency curve is shown in Figure 7 and the regional variation of MSK intensity is shown in Figure 8.

Bedrock Response Spectra
Typical calculated uniform frequency bedrock response spectra are shown in Figure 9.

Site Response Effects
It is well known that local soil effects can have a significant effect on earthquake damage levels. The damage in Mexico City in 1985 was an extreme example and soil effects were very evident in the 1989 Loma Prieta earthquake.

McMaster University, in Canada, has recently carried out a systematic study of site response effects using the methods described in Reference 15. Three groups of 15 earthquakes were used to represent rock outcrop motions. One group, chosen to represent high peak acceleration to peak velocity (a/v) ratios indicative of near field medium sized earthquakes with a high frequency content, was considered suitable to the UK. Four levels of input motion were also considered corresponding to peak velocity values of 0.05, 0.1, 0.2 and 0.4 m/sec. Four soil types and depths were studied.

The results, as shown in Figure 10, have been presented as the ratios of the base shear of a typical structure founded on soil to that of one founded on rock. It is notable that the base shear amplification for soft clay is greater than the other soil types especially at periods greater than 0.4 seconds. At lower periods, however, the amplification is greatest for the 5 m thickness of the loose sand, stiff clay and dense sand. This implies that conventional

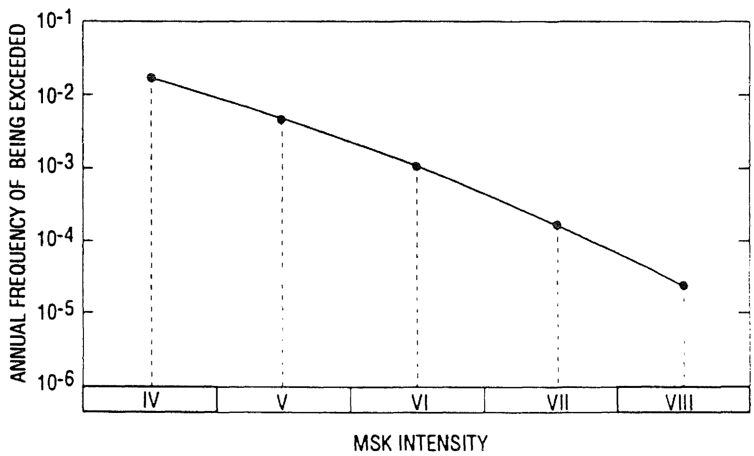

FIGURE 7 CALCULATED FREQUENCY OF MSK INTENSITY

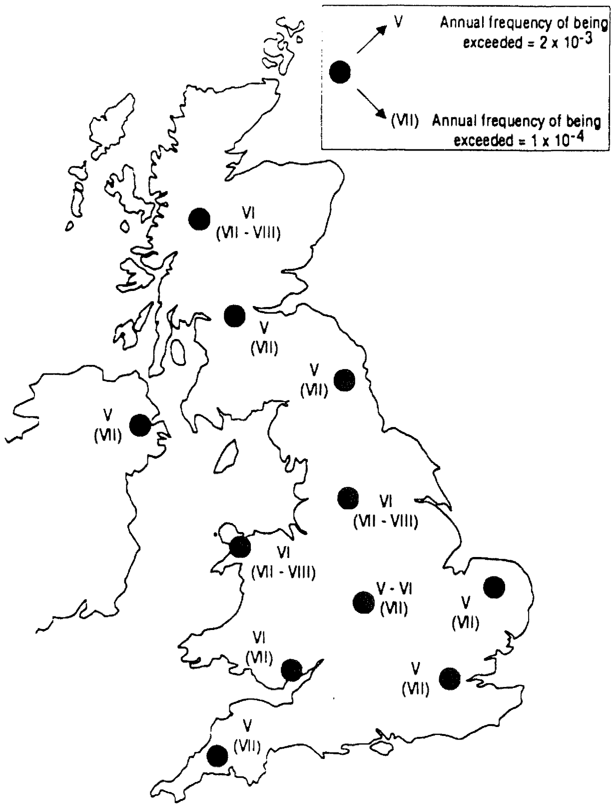

FIGURE 8 REGIONAL VARIATION OF CALCULATED MSK INTENSITY

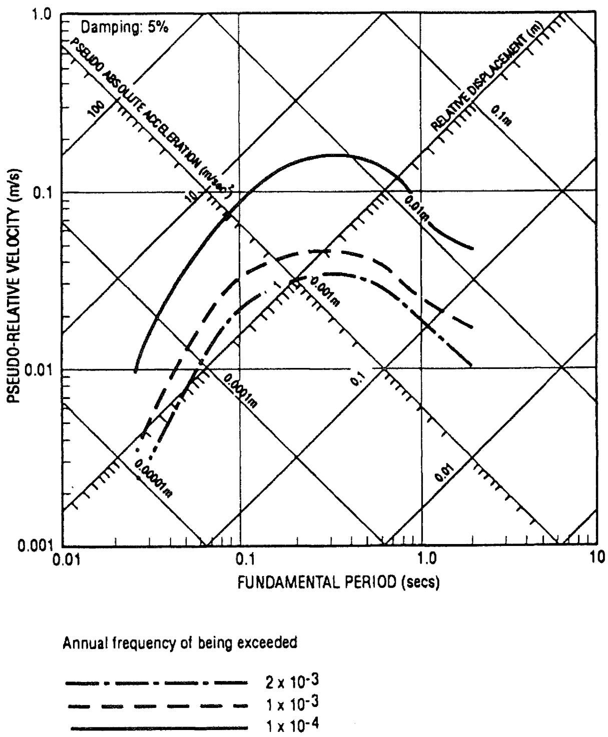

FIGURE 9 CALCULATED UNIFORM FREQUENCY BEDROCK RESPONSE SPECTRA

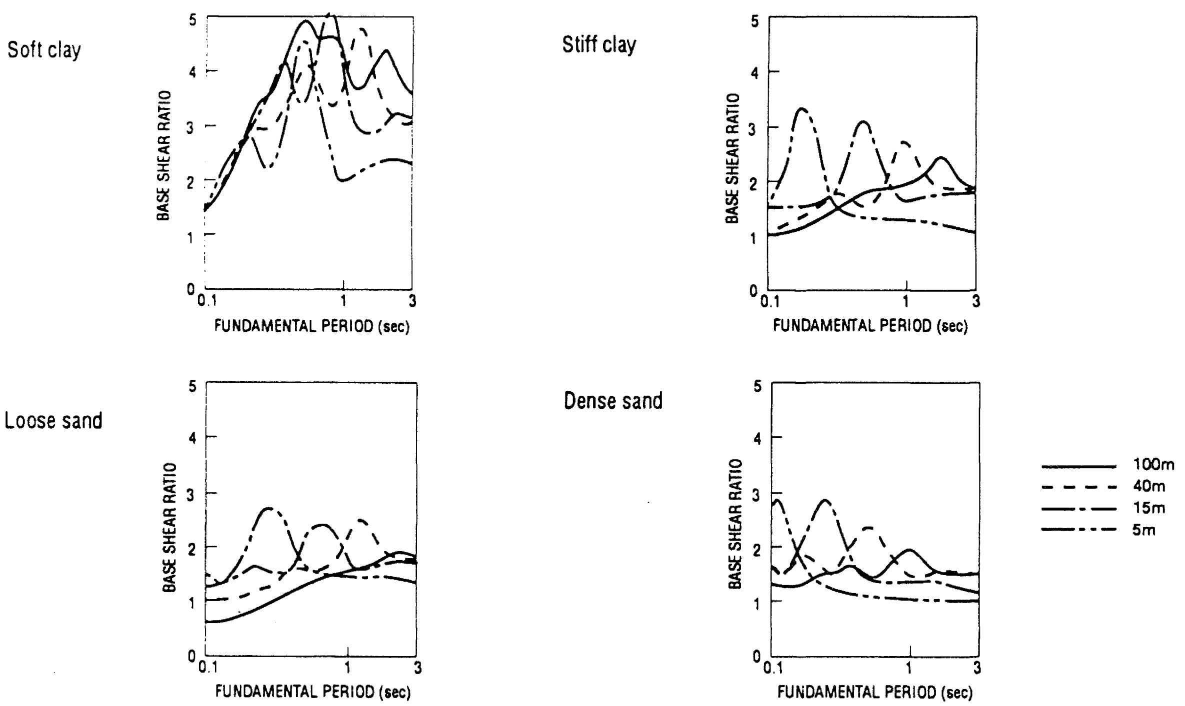

FIGURE 10 CALCULATED BASE SHEAR RATIOS FOR PEAK BEDROCK VELOCITY = 0.5 M/SEC

one to three storey structures will experience more earthquake damage when underlain by relatively thin soil deposits. This was observed in the 1971 San Fernando earthquake [22] and in the 1989 Newcastle earthquake [13]. In 1976, Seed et al [23] published a set of spectral shapes for four soil profiles, namely rock, deep soft soils of 100 to 200 m, deep cohesionless soils of 80 to >300 m and stiff clay soils of 15 to 40 m. The spectral shapes predicted by the McMaster study are similar for corresponding soil conditions.

VULNERABILITY FUNCTIONS FOR BUILDINGS

This section considers the form and type of data available from damage surveys carried out after various earthquakes. This data is held by Cambridge Architectural Research and their methodology [24] for developing vulnerability functions applicable to masonry buildings and reinforced concrete buildings has been followed. For reinforced concrete structures the vulnerability functions have been compared with other published data and with those derived from basic structural calculations.

The Use of Damage Surveys

Traditionally seismic intensity scales have been used to express the level of damage in any particular location. The definition of seismic intensity scales has long assumed that the performance of broad categories of building type is similar, irrespective of location, and the damage levels to commonly occurring building types is used to define various levels of intensity. An initial compilation of earthquake damage surveys in 1986 [7] indicated that significant variations existed between the classification of intensity levels from one survey group to another. However, their assessment of damage distributions within particular building types and the relative damage levels between two building types were consistent across most of the surveys. Collection of a considerably expanded data set of damage surveys since then has enabled further analysis of the vulnerability of a range of building types and, perhaps more importantly, has made it possible to assess the confidence limits with which prediction of future damage levels can be made.

The problem of intensity assignment or damage level can be illustrated using data from the 1989 Newcastle earthquake [13]. Here a survey of the damage to 620 buildings was carried out by re-examining photographs of every building within a given defined area. The building sample consists of about 380 masonry, 140 reinforced concrete and 100 timber. The damage levels, D1 to D5, were assessed in accordance with Table 1 and basically accord to the MSK Intensity Scale definitions. Figure 11 shows the observed damage as a percentage of the total building stock. It can be seen from Figure 11 (a) that the storey height has little influence on damage levels provided there is more than one storey. Figure 11(b) however shows there is a noticeable influence of age on the damage levels to masonry.

It is virtually impossible to relate the damage in Newcastle to ground motion as there were no instruments in the vicinity and there is only a poor understanding of where the epicentre was located. There is, however, confidence that the hypocentre was about 10 km deep.

TABLE 1. DEFINITIONS OF DAMAGE LEVELS AND ASSUMED REPAIR COST RATIOS

Damage Level	Definition for Loadbearing Masonry	Definition for R.C. Framed Buildings	Repair Cost Ratio *
D0 Undamaged	No visible damage	No visible damage	0
D1 Slight Damage	Hairline cracks	Infill panels damaged	0.05
D2 Moderate Damage	Cracks 5-20mm	Cracks 10mm in structure	0.20
D3 Heavy Damage	Cracks 20mm or wall material dislodged	Heavy damage to structural members, loss of concrete	0.50
D4 Partial Destruction	Complete collapse of individual wall or individual roof support	Complete collapse of structural member or major deflection to frame	0.80
D5 Collapse	More than one wall collapsed or more than half of roof	Failure of structure members to allow fall of roof or slab	1.0

* Repair Cost Ratio: Ratio of the cost of damage to reconstruction cost.

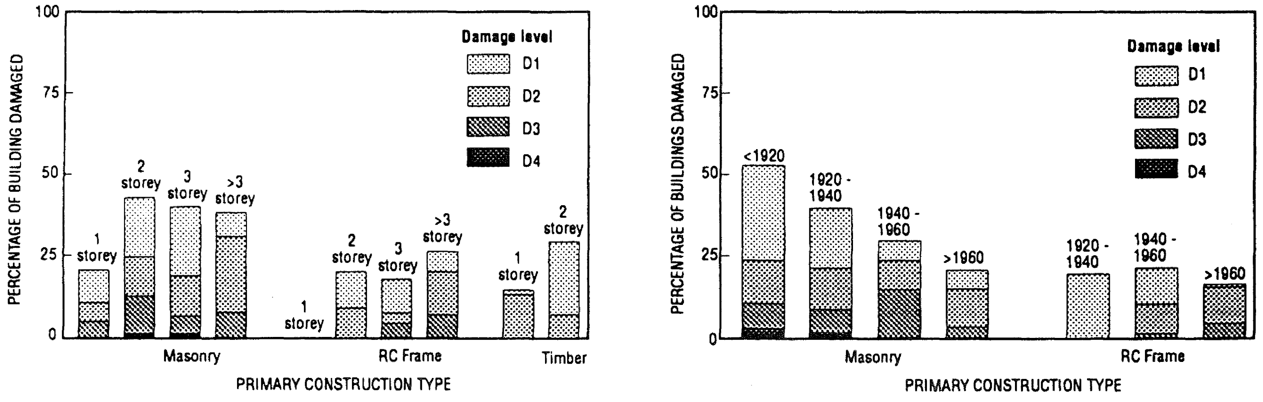

FIGURE 11 EEFIT NEWCASTLE SURVEY: VARIATION OF DAMAGE LEVELS WITH (A) NUMBER OF STORIES (LEFT) AND (B) AGE OF CONSTRUCTION (RIGHT)

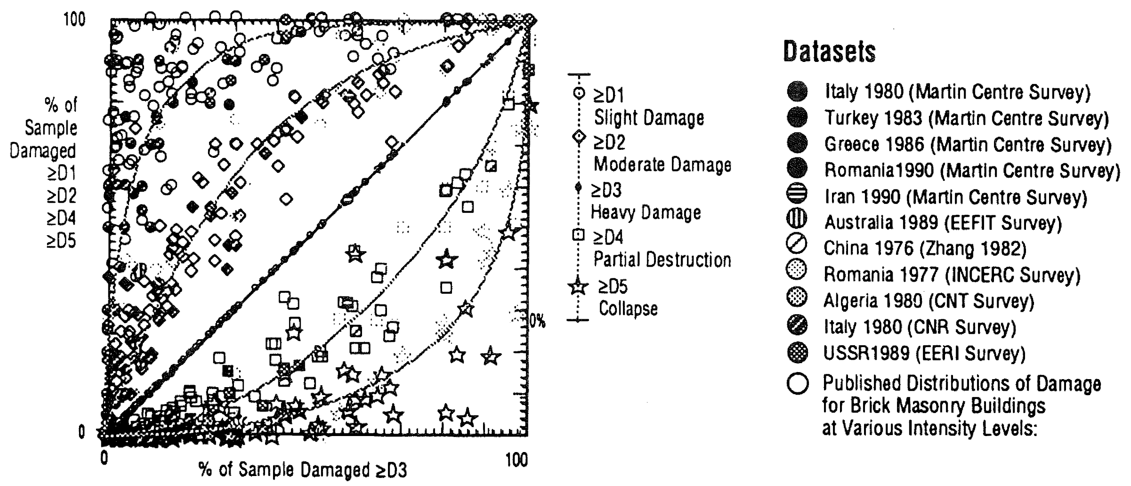

FIGURE 12 EARTHQUAKE DAMAGE DISTRIBUTIONS FOR MASONRY BUILDINGS [24]

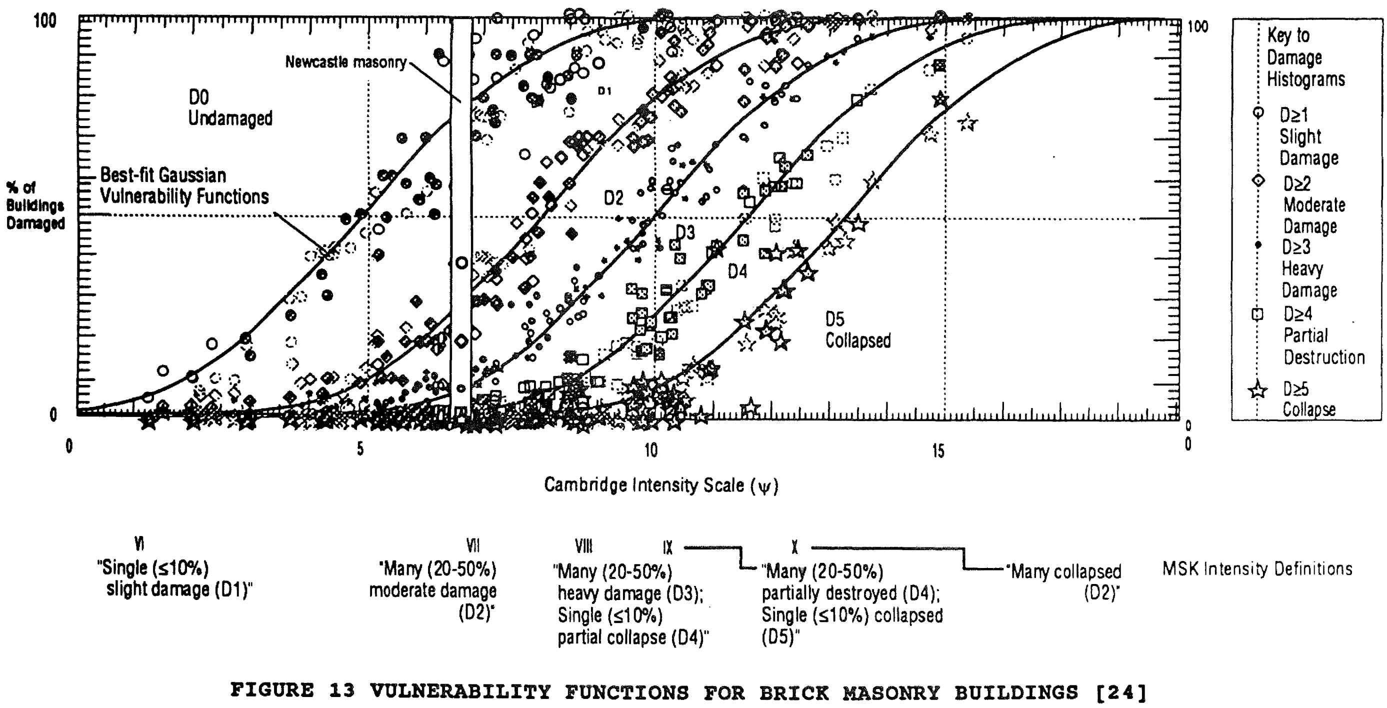

FIGURE 13 VULNERABILITY FUNCTIONS FOR BRICK MASONRY BUILDINGS [24]

Distributions of damage states (presented as cumulative histograms) for the 103 surveys comprising the Cambridge data set of brick masonry buildings are presented in Figure 12. The data are ranked according to the percentage of the sample to have suffered the middle damage state D3 (Heavy damage) or greater. Most distributions given here consist of over 50 buildings, and surveys of less than 20 buildings are excluded as unreliable. Although there is some variation, it can be seen that there is a degree of consistency in the distributions of damage states found in all the survey samples. This diagram displays only the distributions of damage surveyed and does not relate the distribution to any assessment of ground motion. The data appear to conform to a series of curves. These curves can be used to predict the damage distribution if the number of buildings damaged to at least one damage level is known.

The Cambridge Intensity Scale, ψ

Figure 13 shows the damage survey data plotted in order of increasing damage. Superimposed on this data is a set of Gaussian curves, each with the same standard deviation. The horizontal scale is referred to as the Cambridge Intensity Scale, ψ and has been derived to obtain a best fit between the Gaussian curves and the damage distribution data [24].

Relating ψ to MSK Intensity

As described previously the hazard level has been determined in terms of MSK Intensity. To calculate risk using the ψ scale means a relationship between ψ and MSK Intensity must be devised. The definitions of MSK Intensity between VI and X are relatively precise for damage levels to 'Ordinary Brick Houses'. These definitions are superimposed on the ψ scale in Figure 13 at the location where the level of damage best agrees with that indicated by the ψ scale.

Relating ψ to Ground Motion

Several past studies have obtained relationships between ground motion (mostly peak horizontal acceleration) and various intensity scales. The low confidence that can be placed in intensity assignment suggests that these relationships are highly approximate. Where damage distributions are surveyed close to a measured point of ground motion, the relationship between ground motion and damage can be ascertained. Surveys of building damage around locations where strong motion instruments have been triggered has formed part of the Cambridge damage surveying methodology over the past ten years. Some 14 damage surveys have been carried out in the immediate vicinity of recording instruments [24]. Although the data set is limited, the correlation of ψ with several commonly used ground motion parameters is important to indicate which of these parameters gives the best prediction of damage. Acceleration parameters generally appear to be stronger primary parameters than the velocity or duration. The correlation between peak acceleration and ψ has been plotted in Figure 14. For the study presented here the 0.2 second period response spectral value has been used. It may be that for longer period buildings, other period ranges would give a better fit.

Vulnerability Functions for Masonry Buildings

The methodology described above has illustrated a means of relating damage levels for masonry buildings of average condition to ψ. It has also illustrated a method of relating ψ to MSK Intensity and to acceleration. In the risk calculations both routes have been used. The study also required an understanding of the uncertainty to associate with the calculation.

The Applied Technology Council [4] have carried out an "expert opinion" survey of damage levels that may be expected for a given intensity level. For low rise brick masonry for example they have produced a best estimate and high and low estimates of damage. For Intensity VII or greater they agree quite well with those derived using the ψ methodology. For Intensity VI ATC proposes significantly greater damage than the ψ method but the definitions of intensity VI (MSK and MM) indicate the ATC

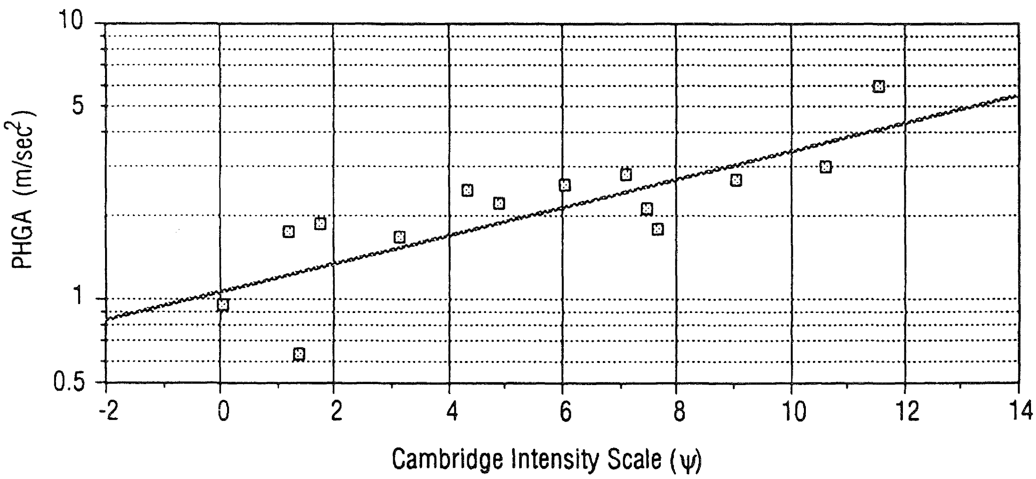

FIGURE 14 CORRELATION OF Ψ TO PEAK HORIZONTAL GROUND ACCELERATION (PHGA)

damage levels are too high. The ATC low and high estimates are about 1 Intensity value to either side of the mean value. This corresponds to a variation in ψ value of about ±2. Figure 14 also shows considerable variability between the ψ value and the acceleration parameters. A variation of ψ of ±2 is within the scatter of this small set of data.

Vulnerability Functions for Reinforced Concrete Buildings

Reinforced concrete (R.C.) buildings have been considered in a similar way to masonry by way of the ψ Intensity scale. Cambridge have plotted their data using the same values of ψ as that derived for the masonry and again Gaussian curves with the same standard deviation match the data. The R.C. curves are similar to those of masonry but are shifted to the right by about 2 ψ units. The ATC assessments for low rise R.C. non-ductile frame structures show a similar damage to intensity relationship that indicated by ψ. By using the ψ to peak ground acceleration relationship shown in Figure 14 and the repair cost ratios in Table 1 a curve for damage cost as a ratio of reconstruction cost can be plotted as a function of peak ground acceleration as shown in Figure 15. Hwang and Jaw [16] calculated the seismic vulnerability of a 5 storey R.C. shear wall structure and have expressed their results in terms of damage level against peak ground acceleration. Their results are also shown on Figure 15 and are seen to predict higher damage at low acceleration levels.

In order to check the likely vulnerability of R.C. buildings simplified calculations have been carried out which relate seismic vulnerability to the minimum lateral strength (required in UK codes) and to data on vulnerability given for code designed buildings given by NEHRP [21].

A lower bound ultimate lateral strength of UK buildings over 2 storeys was assumed to be 1.5% of deadweight which is the current UK code requirement. Recent studies [5] suggest that wind loads would probably impose higher loads, than the minimum requirement, for R.C. buildings over about 20 storeys. There were considerable objections to the minimum lateral strength requirement when it was first introduced and recent proposals to increase the requirement in low rise buildings have also met with resistance. It follows that the 1.5% strength figure is unlikely to be substantially exceeded except perhaps in very tall buildings and in low rise buildings where minimum practical dimensions are likely to govern design, rather than lateral strength. An upper bound lateral strength was therefore assessed to be 2½ times the lower bound strength.

NEHRP [21] specifies the ultimate lateral strength required to withstand a given level of design spectral acceleration. It also gives an estimate of the probability of failure against the peak spectral acceleration experienced in an earthquake as a ratio to the design spectral acceleration. Using these relationships, the damage resulting from a given acceleration was able to be calculated for both the lower bound and upper bound strengths. The results are shown in Figure 15 and are seen to bracket those derived from ψ and those calculated by Hwang and Jaw. It is considered that this exercise lends credence to the ψ vulnerability curves but some structures,

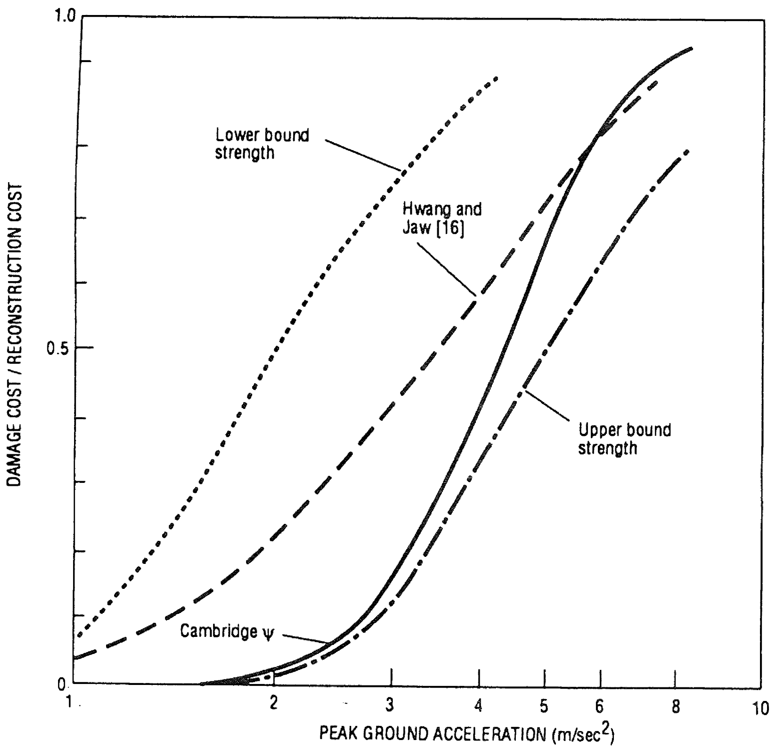

FIGURE 15 COST RATIOS FOR REINFORCED CONCRETE BUILDINGS

particularly those with significant irregularity, may exist that correspond to the lower bound strength and vulnerability conditions.

MICROZONING STUDIES

For the purposes of the study two areas in the UK were chosen, They had above average seismic hazard, an area of about 400 km^2 and a mixture of urban and rural land use. For each area a series of calculations have been carried out to estimate the effects of specific earthquakes. This calculation combined the attenuation relationship, the soil amplification (if appropriate), the distribution of building types and their vulnerability functions. Two sets of calculations were performed, one using MSK Intensity as the hazard parameter and the other using the 0.2 second period response spectral acceleration.

To provide a check of the methodology, three earthquakes of known effects have been studied. They are:

The 1990 Bishop's Castle earthquake.
A magnitude 4.4 M_s at 14 km depth.

The 1983 Liege (Belgium) earthquake.
A magnitude 4.5 M_s at 4 km depth.

The 1989 Newcastle earthquake.
A magnitude 5.5 M_s at 10 km depth.

To examine the effects of an extreme earthquake, by UK standards, a magnitude 6.5 M_s earthquake at a depth of 15 km was also modelled.

Computer maps of both areas were assembled using the Cambridge Architectural Research computer program SISMA. The following geographical data were incorporated -

Ward and Parish boundaries

Soil Type In accordance with the classification in Figure 10

Current Land Use Whether urban, industrial or rural (inc. parks etc).

Historical Development Significant urban areas were zoned together with the identification of central business districts.

Using population statistics from census data the number and distribution of the residential building stock could be estimated from the Ward, the land use and the historical development period. The number and make up of non-residential buildings were estimated in a similar way but many assumptions were required as the available data is in terms of national totals.

Analyses of Specific Earthquakes

The microzoning analyses have been carried out using the MIZAN program developed by Ove Arup and Partners. The program works by considering a grid overlying the area of interest. In this study a 0.5 x 0.5 km grid was used and the program SISMA used to determine the values of the geographical parameters described above at the centre of each grid.

In order to calculate the consequences arising from a specific earthquake the MIZAN program calculates the damage in each grid square. This process consists of the following steps:-

- calculate the value of seismic hazard parameter using the attenuation relationship and appropriate hypocentral distance;
- calculate the soil amplification if appropriate;
- calculate the ψ value corresponding to the seismic hazard parameter;
- determine the fraction of each building type b damaged to at least the damage levels D1 to D5 using the ψ value and the vulnerability function calculate the cost of damage

For all calculations two hazard parameters have been used namely MSK Intensity and 0.2 second period spectral acceleration. The soil amplifications shown in Figure 10 were applied in the spectral acceleration calculation.

Predicted Building Damage

The predicted quantity of damage for the 5 levels of damage D1 to D5 to each of the four earthquakes are represented graphically in terms of % of the total building stock in Figure 16. The results are as follows:-

Bishop Castle type earthquake
The calculation using MSK Intensity as the hazard parameter gives no damage whereas the spectral acceleration calculation shows about £10 million. From the recurrence curve shown in Figure 6, it is estimated that the annual frequency of an earthquake of this size within each area is about 3 x 10^{-4}.

Liege type earthquake
The calculated cost is about £150 million using MSK Intensity and £250 million using spectral acceleration. The actual cost of damage due to the Liege earthquake was about £50 million [17]. As Liege has a similar population to the microzoning areas this damage value is probably appropriate to the areas in question. The annual frequency of a shallow event of this magnitude would be about 1 x 10^{-4}.

Newcastle type earthquake
The calculated costs vary between about £1200 million and £1700 million. The actual reconstruction works of the Newcastle earthquake amounted to about £500 million. Again Newcastle has a similar population to the study areas, but it must be emphasised that the majority of housing in Newcastle comprised single storey bungalows of which about 25% are brick masonry and 75% are timber. If the housing had been 2 storey brick masonry similar to the UK, losses would probably have been noticeably higher. The annual frequency would be about 2 x 10^{-5}.

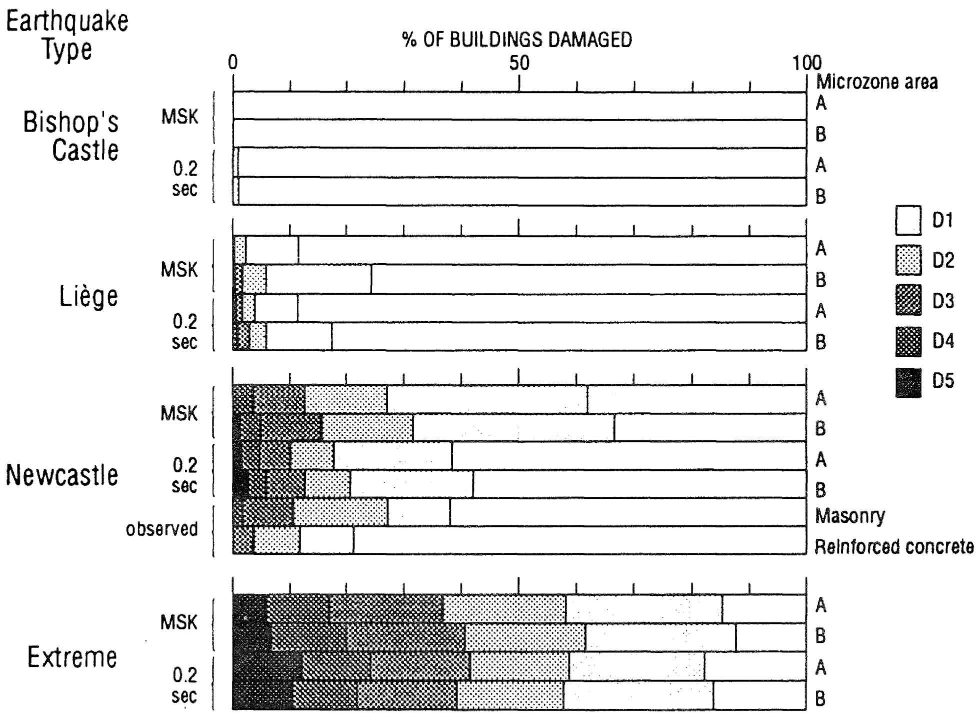

FIGURE 16 PREDICTED BUILDING DAMAGE FOR SPECIFIC EARTHQUAKES

Extreme earthquake
The calculations show extensive damage with total costs of about £4 billion which amounts to about half the total value of the building stock. The annual frequency of an event of this magnitude occurring in the vicinity of each area is less than 1 x 10^{-7}.

Predicted Fatalities

One of the worst consequences of earthquakes causing structural damage is the risk to the population of death and injury. For the purposes of comparing earthquake risk to other risks of life loss, casualty predictions were made from the estimates of damage from the specific events considered. The method used for human casualty prediction was based on those developed at the University of Cambridge, Department of Architecture [8].

There are large uncertainties involved in predicting human casualties in earthquakes. A review of literature shows that prediction of numbers of fatalities are generally more accurate for more damaging earthquakes (numbers of buildings damaged ≥ D3 of more than 10,000) than for moderate events. This is because at high levels of damage the deaths and injury due to structural damage form a greater percentage of the total than they do at low levels. At low levels of damage to the building stock, as are being considered here, the highest proportion of casualties are caused by damage to elements other than buildings (e.g. garden walls, street signs), by non-structural damage to buildings (glazing, cladding, interior building contents) and other causes. Predicting human fatalities can therefore only be very approximate.

Between 0 and 500 fatalities with a best estimate of around 10 were predicted for the Liege type earthquake. The actual number of people killed in Liege was 3. Between 100 and 4000 with a best estimate of around 500 were predicted for the Newcastle type event and in fact 12 people were killed. If the earthquake had not occurred on a holiday that number could easily have reached 100. It would have increased again if the housing building stock had been more similar to that of the UK (i.e. 2 to 3 storey masonry). The predicted fatalities, especially the upper estimate, therefore appear to be too high.

ANNUAL RISK TO BUILDINGS

As stated in the introduction risk is defined as the "level of damage due to a specific earthquake or which may be expected at a prescribed rate of occurrence". It is also stated that risk is the integration of hazard times vulnerability. This part of the paper presents the calculated risk, in terms of annual cost as a ratio of reconstruction cost, for both masonry and R.C. Structures. The sensitivity of the result to uncertainty of the input parameters has also been examined.

The annual cost calculation is similar to that used in the microzoning analysis for a specific building type. In this case however the calculation is integrated over the full range of hazard values each with its own level of annual frequency. Figure 17 illustrates this calculation. It shows the results for damage to masonry structures arising from average seismic hazard in the UK in terms of 0.2 second period spectral acceleration for a site underlain by 5 m of dense sand. The overall annual cost as a

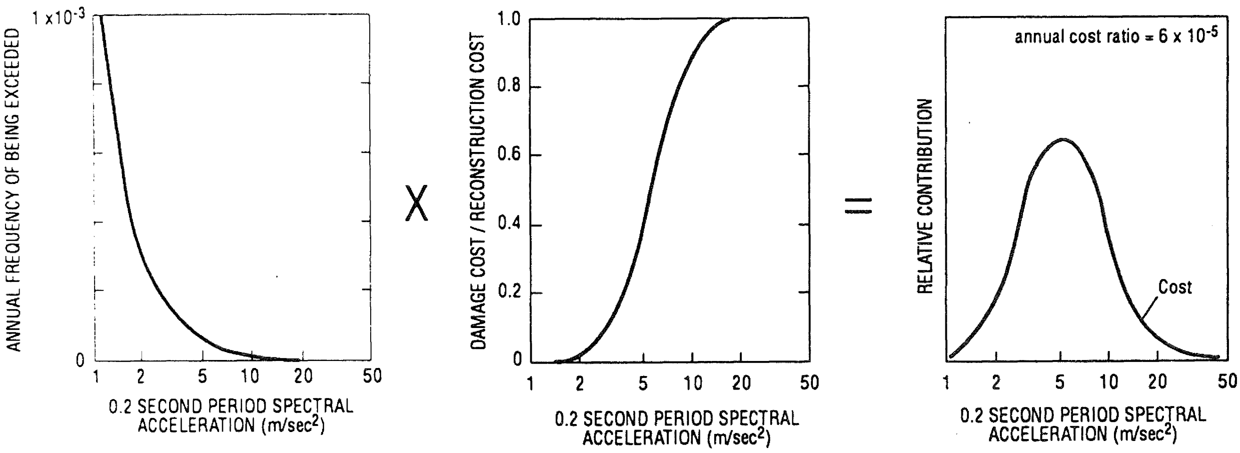

FIGURE 17 CALCULATION OF ANNUAL COST RATIO

ratio of reconstruction cost is calculated to be 6 x 10^{-5} and arises mainly from a spectral acceleration of about 5 m/sec^2 which has an annual frequency of being exceeded of about 5 x 10^{-5}. This implies that a very long period of observation is required before a sensible empirical measure of earthquake damage can be made.

Masonry Buildings

To study the effects of uncertainty in the hazard and vulnerability parameters, a parametric study of the annual cost of masonry buildings subject to the average UK seismicity has been carried out using both MSK Intensity and acceleration. The results of this study are shown in Figure 18 in terms of annual earthquake damage cost as a ratio of reconstruction cost.

MSK Intensity. To study the effect of the uncertainty of the relationship between ψ and MSK Intensity the calculation has been repeated with a variation of ψ to MSK Intensity of $\pm 2\psi$ units (approximately 1 unit of Intensity). As can be seen this variation effects the annual cost ratio by about a factor of 2.5. The variation of the seismic hazard across the county has been calculated by using the locations with the lowest and the highest hazard level in Figure 8. The resulting annual cost ratios are shown in Figure 19 and again they are effected by about a factor of 2.5. This variation is well within the possible band of uncertainty.

Spectral acceleration. Site soil response effects should be explicitly considered when considering spectral accelerations. As shown in Figure 18 the resulting annual cost varies from 2 x 10^{-5} at rock sites up to 16 x 10^{-5} for a site comprising 5 m of stiff clay over bedrock. This variation is very significant and has a greater effect than the other uncertainties. Only 5 and 15 m deep soil sites have been considered here

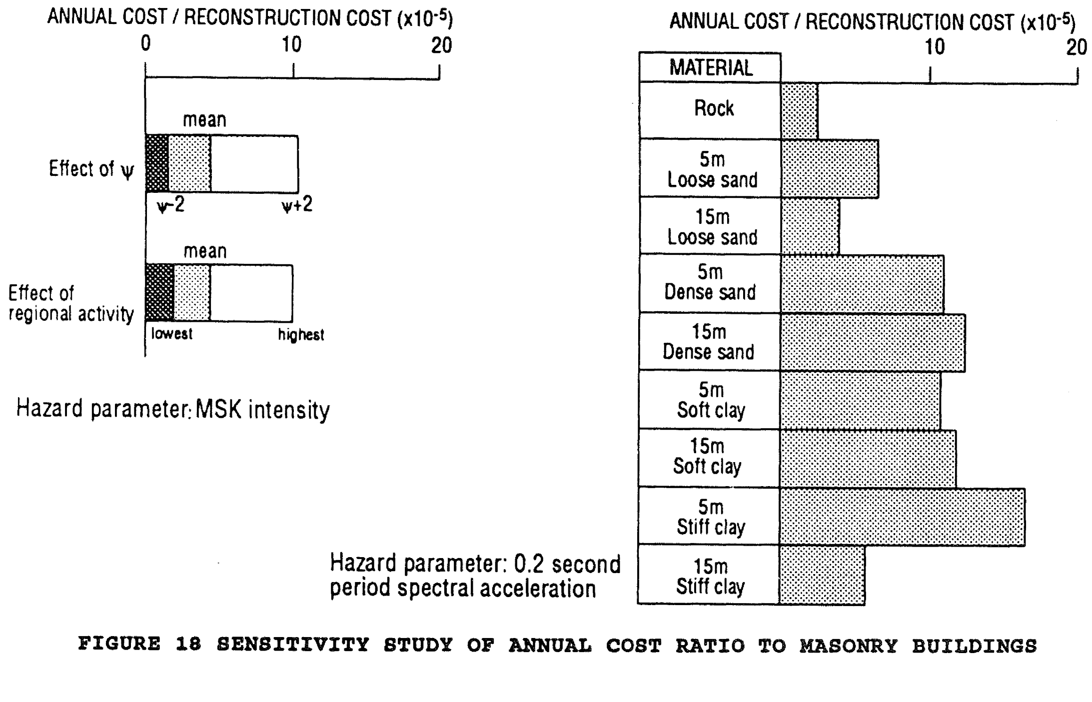

FIGURE 18 SENSITIVITY STUDY OF ANNUAL COST RATIO TO MASONRY BUILDINGS

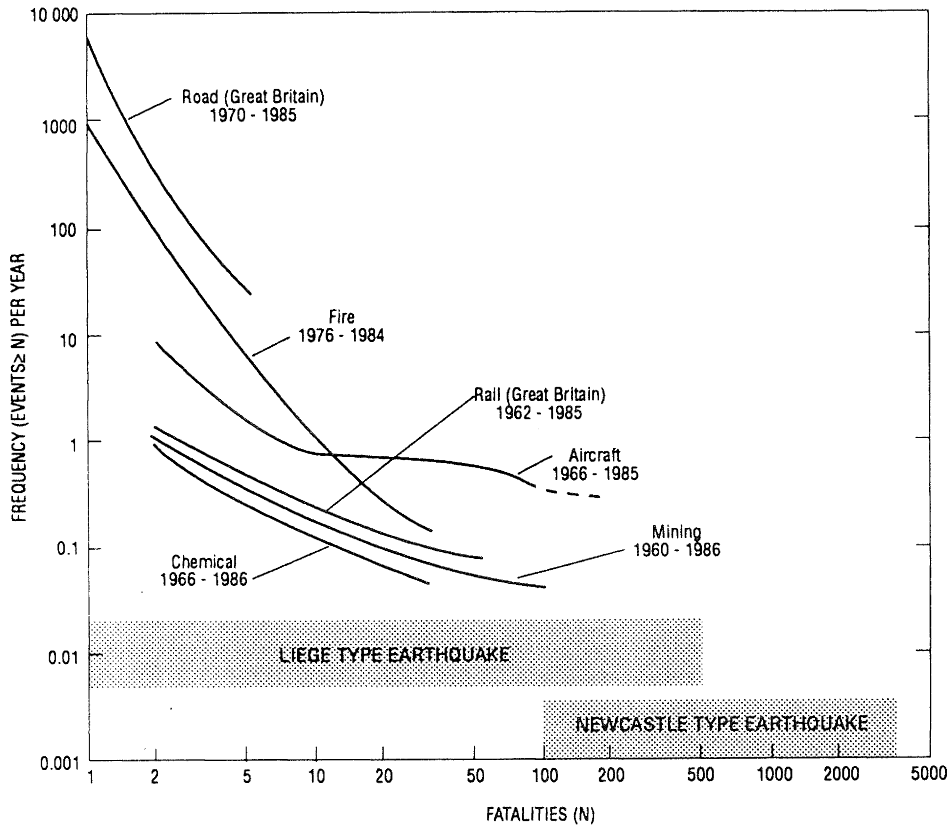

FIGURE 19 PREDICTED FATALITIES IN THE UK DUE TO EARTHQUAKES AND THOSE OBSERVED FROM OTHER HAZARDS [14]

because they have the greatest effect on low period structures and generally they are more common in the UK than deeper soil sites.

Reinforced Concrete Buildings

A similar parametric study to that described above has been carried out for reinforced concrete buildings. The relative effects of the uncertainty are similar to that for masonry structures but the annual cost ratios to R.C. structures are calculated to be about a third of those for masonry.

COMPARISON WITH OTHER RISKS

Financial Cost

To put the costs of earthquakes in context the costs of other types of natural hazard have been considered. Damage of the order of the Newcastle earthquake has occurred twice in the UK during the past five years because of storms. Considering that the chance in the UK of a Newcastle type earthquake occurring near a major population centre is 1 in 500 per year, the financial costs associated with earthquakes are thus very small in relation to costs due to storm damage.

The overall annual cost calculations however show annual earthquake costs as a ratio of reconstruction cost of around 2 to 5 x 10^{-5} which corresponds to annual costs in the UK of between £40 million to £100 million. On the basis of insurance settlements in the past 10 years all types of weather incidents including gales, snow and floods, add up to about £600 million per year (at 1990 prices). Two very severe weather incidents have occurred during this period and therefore this figure may be above the general trend. In 1990 insurers paid about £500 million in subsidence claims and about the same amount was paid in fire claims.

It therefore follows that the annual estimate of £40 million to £100 million for earthquake losses, while it may be an order of magnitude too high, is still a modest cost compared to observed weather, fire or subsidence claims. It must also be emphasised that these observed figures are not directly comparable with the earthquake predictions. If similar prediction exercises were to be carried out for any of these other hazards then it is probable that the predicted integrated cost over a long time period would be considerably higher than that observed over the past few years.

Risk of Fatalities

In the United Kingdom there are no formal guidelines on the levels of tolerable and intolerable risk to both the individual and to society at large. Statistics of fatalities are maintained however and Figure 19 shows a series of F-N curves observed in the UK from a variety of causes recorded over the 15 to 25 years prior to 1986 [14]. These curves plot frequency of an event against the number of casualties it causes. The results of the predictions of fatalities from the microzoning studies are also shown in Figure 19. Their frequencies were arrived at by assuming there are about 100 population centres in the UK as large or larger than those in the microzoning areas. The predictions for both types of earthquake are seen be lower than those observed from other hazards.

DISCUSSION

Two circumstances in which earthquakes become a consideration in the UK are:-

i) Where the consequences of failure of a structure are so alarming in terms of cost or casualties that failure should be extremely unlikely. This is already the case for nuclear installations in the UK.
ii) Where a structure is particularly vulnerable to earthquake loading. The circumstances when a particular type of structure may be vulnerable to earthquake loading was clearly demonstrated in the Newcastle earthquake [13] where there were at least two cases of "soft storey" failures. The annual cost calculations also highlight that buildings may be particularly vulnerable when the local soil period matches the structural period.

While the study described in this paper is only directly applicable to the UK it is considered that the results are relevant to many areas of the world having low seismicity. Even though the general risk from earthquakes is low a check is required to prevent buildings being constructed with inadequate seismic resistance. This may take the form a checklist to see if there is a particular feature, for example a "soft storey", and if so then additional design calculations would be necessary. To achieve comparable reliability to that implied by codes of practice in areas of high seismicity the earthquake loading used in design calculations should correspond to an annual frequency of about a third of that used in those areas [5]. Provisions should also be enacted to ensure that new structures are sufficiently robust. This could be achieved by having minimum requirements for structural tying and continuity.

CONCLUSIONS

In areas of low seismicity the risk to society in terms of both cost and fatalities from damage to conventional structures is sufficiently low not to cause concern.

For some existing structures the risk for earthquakes may be many times higher than the average. These conditions may result from a correspondence of soil and structural period or from a particularly vulnerable type of structure.

Structures whose failure is particularly unacceptable to society, for example buildings of great national or historical importance or hazardous installations, should be checked against earthquake loading criteria.

New buildings, and existing buildings undergoing significant repair or alteration, should be subject to minimum requirements to ensure robustness and assessed against a basic earthquake checklist so that particularly vulnerable features are identified and addressed.

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