EARTHQUAKE HAZARD AND RISK IN REGIONS OF LOW TO MODERATE SEISMICITY

J.W. Pappin
Arup

1 INTRODUCTION

Historically building design in many parts of world does not consider seismic loading. While this is clearly not appropriate for regions of high seismicity it is probably sensible for regions of low seismicity. The question addressed by this paper is whether the cut-off level for seismic design as proposed by the US International Building Code (IBC) is reasonable.

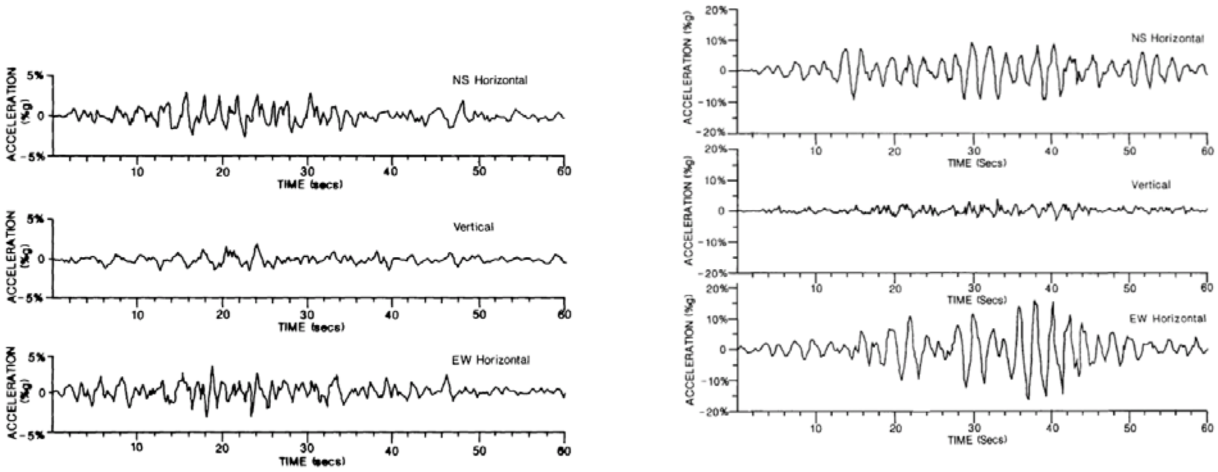
This paper presents some key issues regarding the nature of seismic ground motion hazard and how to assess whether it is sufficiently large to require it to be considered in the design of buildings. It begins by summarising some observations from the 1985 Mexico City and 1989 Newcastle earthquakes with regard to building damage and site response effects. These observations are followed by an overview of seismic hazard and risk studies carried out by the author for the United Kingdom, Hong Kong and the Malay Peninsula. These studies were carried out in the early 1990's, 2000's and 2008 respectively. Partly because of this range of timing, and the widely different nature of the building stock, the methodologies used for these studies have developed. The underlying results however show that the IBC gives reasonable guidance as to when seismic ground motion can be ignored.

2 OBSERVATIONS FROM TWO PAST EARTHQUAKES

2.1 THE 1985 MEXICO CITY EARTHQUAKE

The 1985 Mexico City earthquake was a classic example of extreme site response effects and the disastrous effects on buildings when the period of the ground motion approximately matches that of the first mode of the buildings (Steedman *et al.*, 1986; Booth *et al.*, 1986). This magnitude 8.1 event was located more than 400 km from Mexico City and, apart from damage near to the coastal epicentral region, caused no major damage except for that at Mexico City. In Mexico City itself the damage was limited to the city centre area located on old lakebed underlain by about 30m of extremely plastic clay derived from volcanic ash. Ground motions were recorded both within the lakebed area and in the surrounding rock areas and these are reproduced in Figure 1. It can be seen that the horizontal ground motion is very much larger at the lakebed site and is periodic in nature. The corresponding response spectra are shown in Figure 2. Clearly the lakebed ground surface motion has been dramatically amplified by the ground at a frequency of 0.5Hz i.e. at a fundamental period of 2 seconds. This energy level seriously exceeded the capacity of the buildings and a large percentage of buildings in the height range of 10 to 17 storeys was heavily damaged (Figure 3 shows a serious example) as shown in Figure 4.

The Mexico City experience demonstrated the importance of site response effects and of the correspondence between the seismic ground motion period or frequency content and that of the building stock when assessing damage. It must be noted that various elements conspired here to make this event so damaging at such a large distance from the epicentre. These are that the ground motion in the underlying rock contained significant energy at periods of 0.5 to 2 seconds as shown in Figure 2; the very soft volcanic clay soil in the lakebed was remarkably elastic due to its extremely high plasticity leading to a huge amplification over a small period range and that there were many high rise buildings within Mexico City.



Rock site

Lakebed site

Figure 1: Ground surface motion records recorded at Mexico City in 1985 (Booth *et al*., 1986)

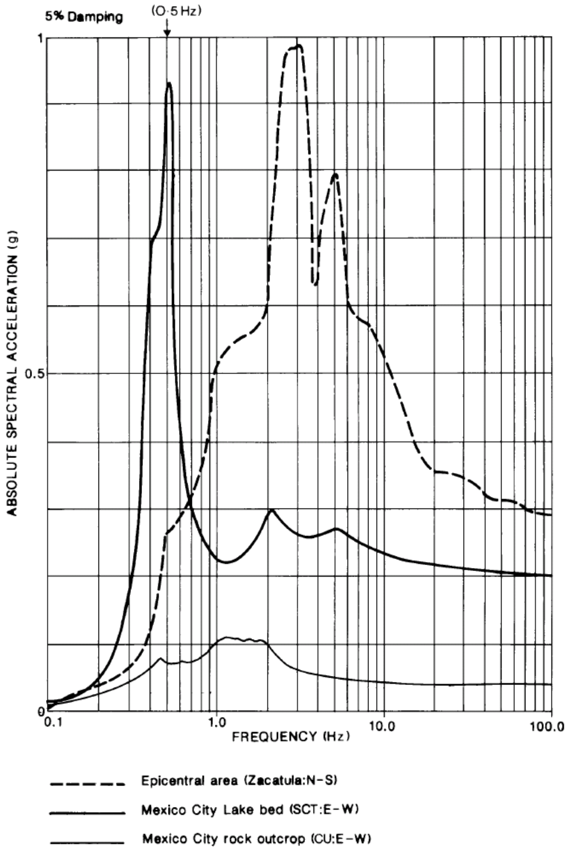


Figure 2: Response spectra of recorded ground motions In Mexico City in 1985 (Booth *et al*. 1986)

Figure 3: Example of building collapse in in Mexico City in 1985

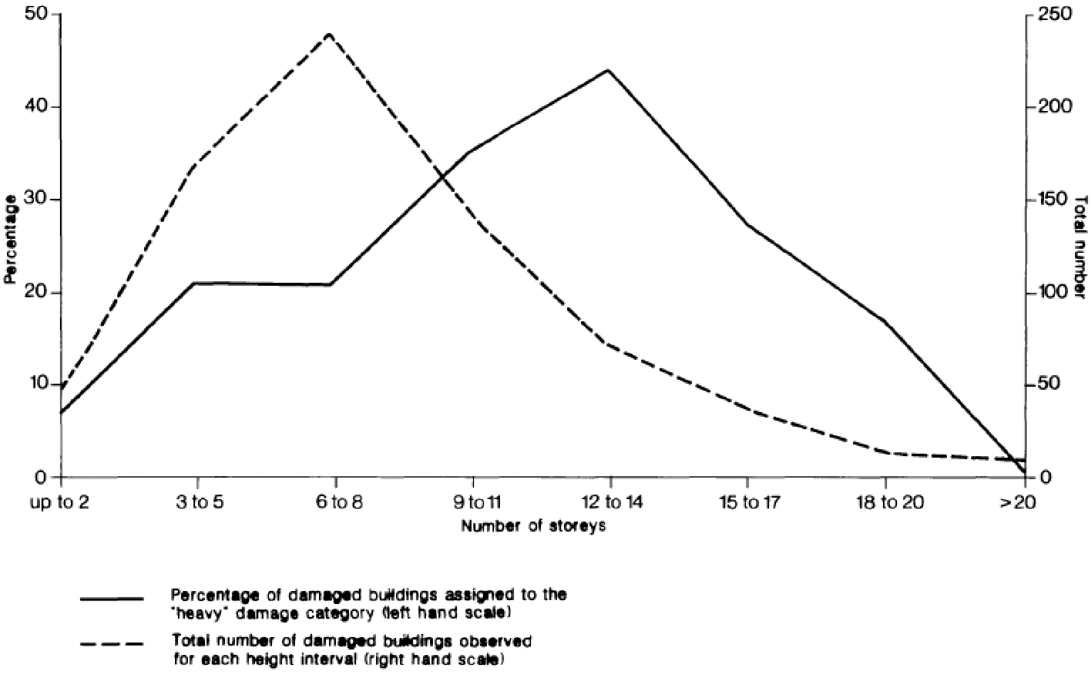


Figure 4: Percentages of heavy damage to buildings against building height in the 1985 Mexico City event

2.2 THE 1989 NEWCASTLE EARTHQUAKE

The Newcastle earthquake in late 1989 (Pappin *et al.*, 1991) was at the other end of the range of damaging earthquakes and was quite conventional in comparison to the Mexico City event. It comprised a magnitude 5.6 that occurred within 20km of a regional city having a population of about 380,000. Damage was mainly limited to unreinforced masonry buildings (see Figure 5).

Figure 5: Examples of the more serious building damage in the Newcastle 1989 event

The author visited the damaged area after the event and undertook systematic damage surveys of selected streets within the city. 628 buildings were photographed and examined from their exterior and the damage levels assessed to be up to partial collapse. Figure 6 shows an overview of the observed damage percentages for unreinforced masonry, reinforced concrete and timber buildings. It is interesting to note that the damage percentages are relatively constant for buildings over 1 storey and that the damage to unreinforced masonry buildings increases for buildings over 50 years old.

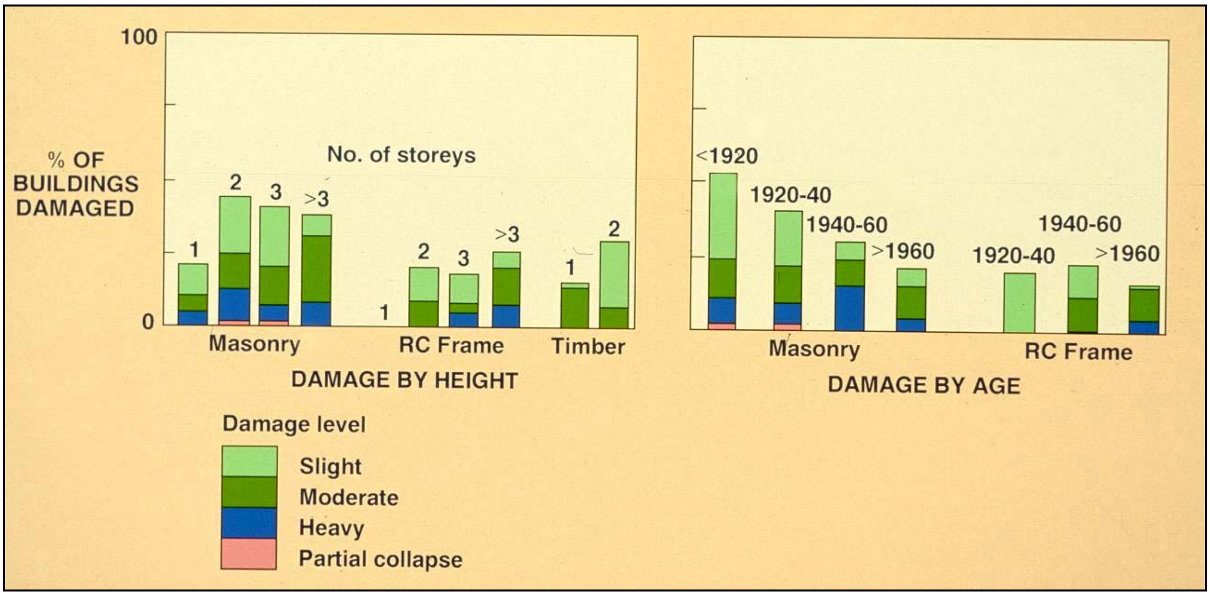


Figure 6: Summary of building damage survey of 628 buildings in Newcastle

Site response effects were not a major feature in the 1989 Newcastle event. Generally the soils were relatively competent but it was noticed that there was greater concentration of damage towards the edges of the soil deposits (Chandler *et al.*, 1991) which is somewhat expected given that the amplification of high frequency ground motion by shallow soil deposits will lead to greater damage to the predominantly low rise building stock that existed at Newcastle.

2.3 COMPARISON OF GROUND MOTIONS WITH CODE VALUES

While the seismic ground motions were not recorded at Newcastle, estimates were made using appropriate attenuation relationships for rock outcrop ground motion and also making allowance for local site response effects (Pappin *et al.*, 1991). Figure 7 shows the range of estimated ground motion plotted as acceleration response spectra against building period. Also shown in the figure is the Mexico City lakebed ground motion and the UBC Zone 1 and Zone 4 design spectra which were appropriate at that time to Newcastle and Mexico City (including allowance for local site conditions) respectively. It should be noted that the UBC ground motions are appropriate for a ground motion having a 10% chance of being exceeded in the next 50 years. It can be seen from Figure 7 that the Newcastle ground motions are likely to be larger than the code estimate for building periods less than about 0.4 seconds corresponding to buildings of about 3 storeys or less. The Mexico City ground motion can be seen to be generally less than the design motion except at the extreme peak observed about a building period of 2 seconds. While the Newcastle and Mexico City response spectra appear to be of a similar order when plotted as acceleration it will be shown later that they are significantly different when it comes to damage potential.

3 REVIEW OF THREE SEISMIC HAZARD AND RISK STUDIES

The author has been involved with three seismic hazard and risk studies as follows

1: United Kingdom completed in 1993

2: Hong Kong complete in 2004

3: Malay Peninsula completed in 2008

Hazard is defined as the level of ground motion whereas risk is defined as the resulting amount of damage. While hazard is quantified in terms of ground motion that has a certain probability of occurring within a prescribed amount of time (conventionally the next 50 years), risk can be expressed in a variety of ways. Risk can be described as the amount of damage or damage as a percentage of the total area, the cost of the damage or percentage cost of original construction cost or as a measure of casualties as either a fraction or number.

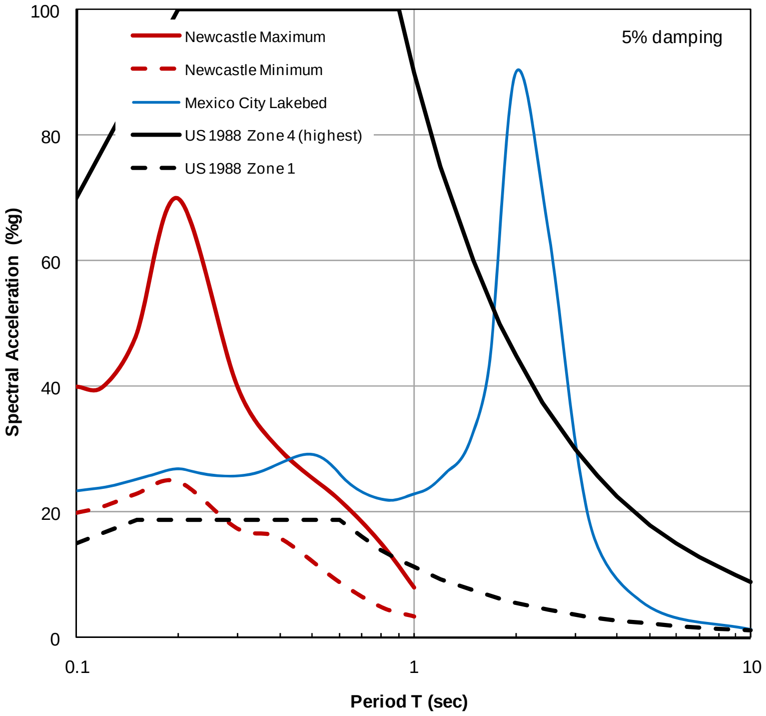


Figure 7: Comparison of the estimated Newcastle surface ground motion with Mexico City and the UBC Zones1 and 4.

3.1 UK STUDY

The UK study involved firstly quantifying the hazard and secondly estimating the vulnerability of the building stock to various levels of ground motion. The project was sponsored by the UK Government as part of its preparation for the introduction of Eurocode and a summary is given in Arup (1993) and in Pappin (1991). While it is well established that the UK does not have large seismic hazard and risk it has suffered some damage in earthquakes over the years and an example is shown in Figure 8. However it should be noted that this 1884 event is considered to be the most damaging earthquake to have been experienced in the UK. In the past 200 years the UK has a very complete written historical record and all earthquake events greater than magnitude (M_S) 4 between 1800 and 1990 are shown in Figure 9.

Two measures of seismic ground motion were used to represent the hazard and also to calculate the risk, namely Intensity and the 0.2 seconds spectral acceleration. Given that the majority of UK building stock is low rise for residential, commercial and industrial purposes the use of intensity scales (such as MSK) was relevant and directly applicable. An example of a continuous damage function against intensity for unreinforced masonry structures is shown in Figure 10. The data shown on this figure was largely derived from previous work by Coburn & Spence (now published in its 2nd edition in 2002). The data from the 1989 Newcastle earthquake is included in this figure and is relevant as the older building stock in Newcastle is extremely similar to that in the UK built at the same time. The most significant part of this figure is the interrelation between the various damage levels. For example, it can be seen that if 20% of the building stock is experiencing Heavy Damage, about another 30% experiences Moderate Damage and about another 40% Slight Damage.

A relatively simplistic Geographical Information System (GIS) was set up for two areas of the UK and Figure 11 schematically shows the layers that were considered to evaluate the damage to these two areas given that a range of three earthquakes was to occur. Figure 12 shows the results for these events, namely a M4.4 at 14 km depth (Bishop’s Castle), a M4.5 at 4 km depth (Liege, see Booth, 1984) and the 1989 Newcastle event.

Figure 8: Example of earthquake damage in the UK

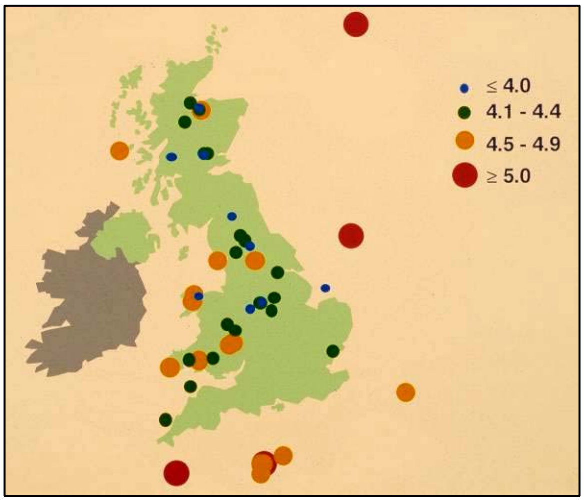


Figure 9: Earthquakes in the UK from 1800 to 1990

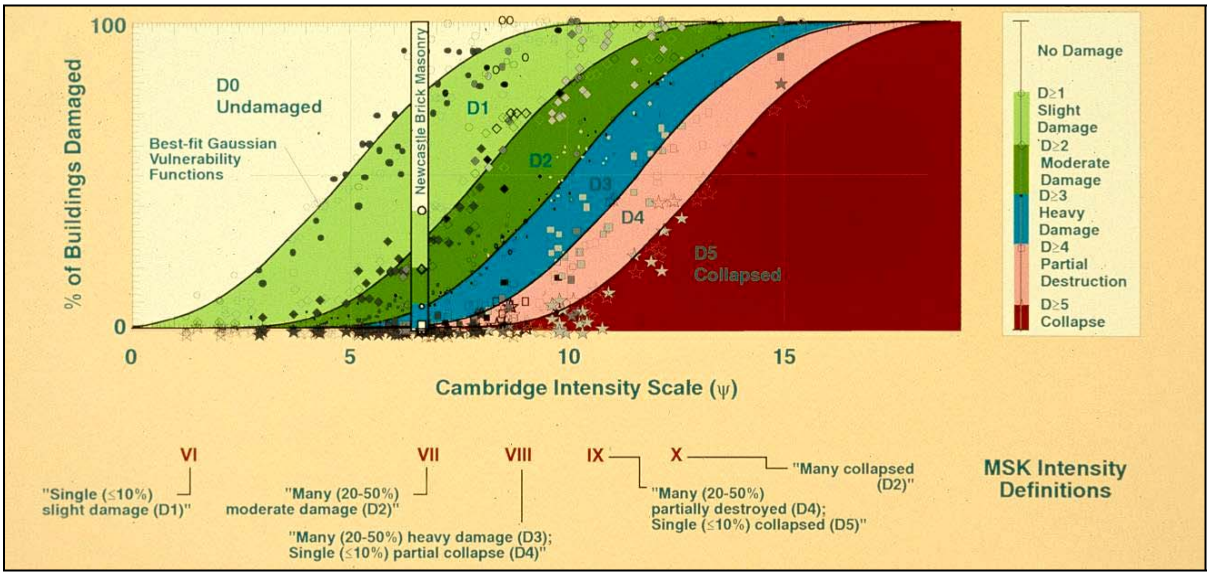


Figure 10: Vulnerability function for unreinforced masonry buildings

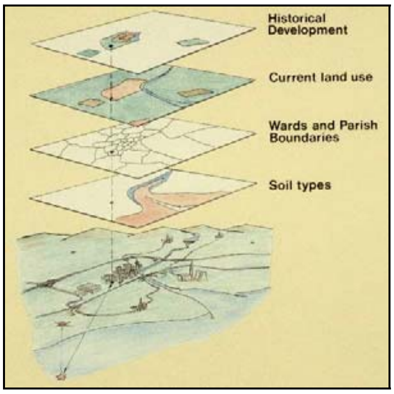


Figure 11: GIS system

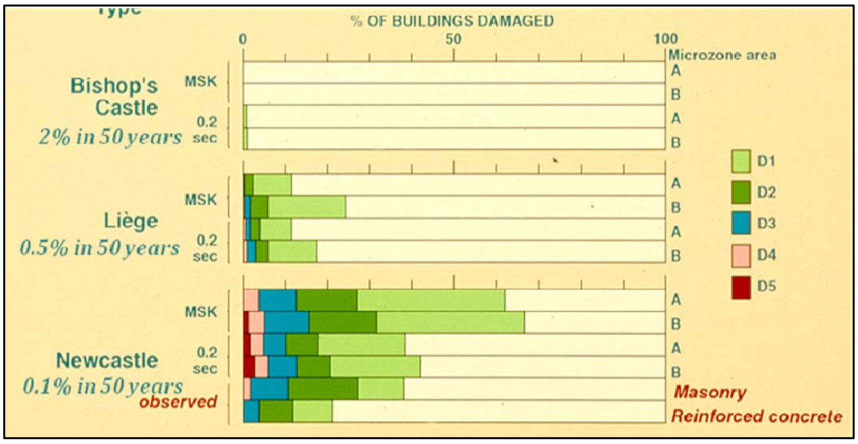


Figure 12: predicted damage percentages for different earthquakes

The probabilities of these ground motions occurring are really quite low and are also shown on Figure 12. By integrating these results with time for all major conurbations in the UK an estimate of the annual cost and predicted fatalities was able to be made and the results are shown in Figure 13.

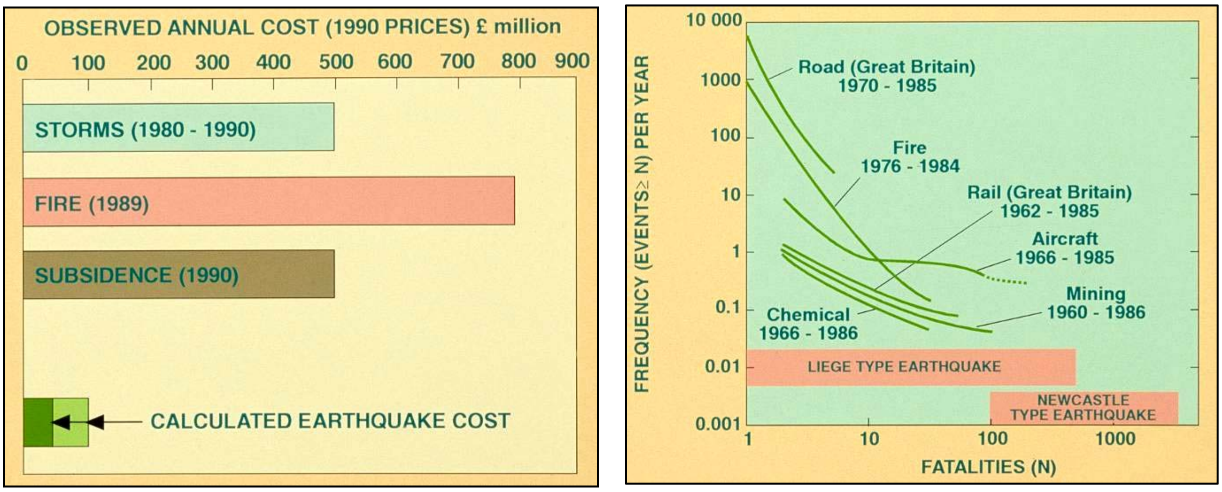


Figure 13: Comparison of calculated seismic risk in the UK to other existing risks

Figure 13 shows that the calculated risk from seismic ground motion in terms of cost is significantly lower than other existing risks and in terms of fatalities is comparable to other risks. It was therefore concluded that the risk to buildings was generally low and that no action is generally required for the design of future ordinary buildings. In accordance with pre-existing practice however especially hazardous structures such as chemical and nuclear installations buildings should be designed for containment against extreme seismic loading (for example a 0.5% chance of being exceeded in the next 50 years).

3.2 HONG KONG STUDY

The Hong Kong study was carried for the Hong Kong Government from 2002 to 2004. Seismic design criteria had matured somewhat in the intervening years (e.g. FEMA 273, 1997, and FEMA 356, 2000) and performance based design of buildings was becoming established with target objectives as shown in Table 1.

Table 1: Performance based design targets

Probability of being exceeded	Likelihood in design life	Acceptable Damage
50% in the next 50 years	Likely	Slight
10% in the next 50 years	Unlikely	Repairable
2% in the next 50 years	Extremely unlikely	No collapse

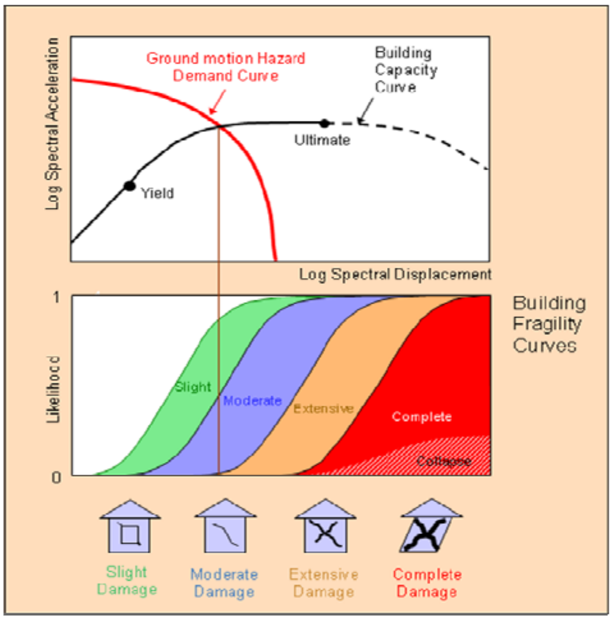


Figure 14: Schematic displacement based methodology used by HAZUS

The methodology used in Hong Kong study was based on the displacement based approach recommended by HAZUS (FEMA, 2000 and 2003). The key elements of this approach are shown schematically in Figure 14 (Pappin *et al.*, 2005). In the upper part of the figure the ground motion hazard is expressed in terms of a demand spectrum which is the response spectrum plotted as spectral acceleration against spectral displacement. This curve is then superimposed on a building capacity curve that is ideally derived from a static pushover analysis of the building structure. Building fragility curves also need to be established based on allowable drift ratios and yield of vertical load bearing elements and are also expressed as a function of spectral displacement and the form of these curves is shown in lower part of the figure. Interestingly this form is very similar to that used in the UK study as shown in Figure 10.

The seismic hazard derived for Hong Kong in terms of bedrock ground motion is presented in Free *et al.*, 2004. As shown in Figure 15 it was found that the level of seismic activity in Hong Kong is very similar to that for the more seismic areas of Eastern USA and substantially higher than that for the UK.

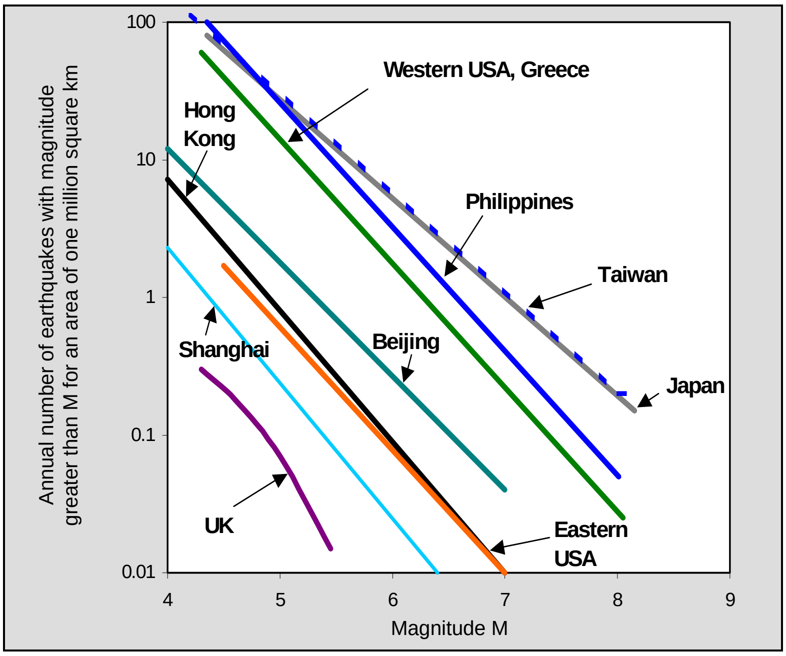


Figure 15: Comparison of observed seismicity rates in various regions of the world

An understanding of site response effects was required and the extensive data base held by the Hong Kong Government was explored and about 1200 boreholes selected and classified in accordance with the US methodology (e.g. IBC, 2009) as shown in Table 2. These classifications combined with the known geology and topography enabled a soil class zoning map to be estimated for region as shown in Figure 16.

Table 2: US Soil classification system (logarithmic average in upper 30m of deposit)

Site Class	Description	Shear wave velocity (m/s)	SPT N value (Blows/300mm)	Undrained shear strength (kPa)
A	Hard rock	>1500	-	-
B	Rock	760 to 1500	-	-
C	Very dense or stiff soil or weak rock	360 to 760	>50	>100
D	Dense or firm soil	180 to 360	15 to 50	50 to 100
E	Loose or soft soil	<180	<15	< 50

Several boreholes were selected from each soil class and site specific non-linear time domain dynamic site response analyses carried out using earthquake time histories scaled to match the bedrock response spectra appropriate to each of the ground motion probabilities as listed in Table 1. Full details are presented in Pappin *et al.*, 2004. The resulting ground surface response spectra for 10% in the next 50 years are presented in terms of demand spectra in Figure 17. It should be noted that demand spectra are the same as the velocity response spectra against building period (grey dashed lines) rotated by 45 degrees.

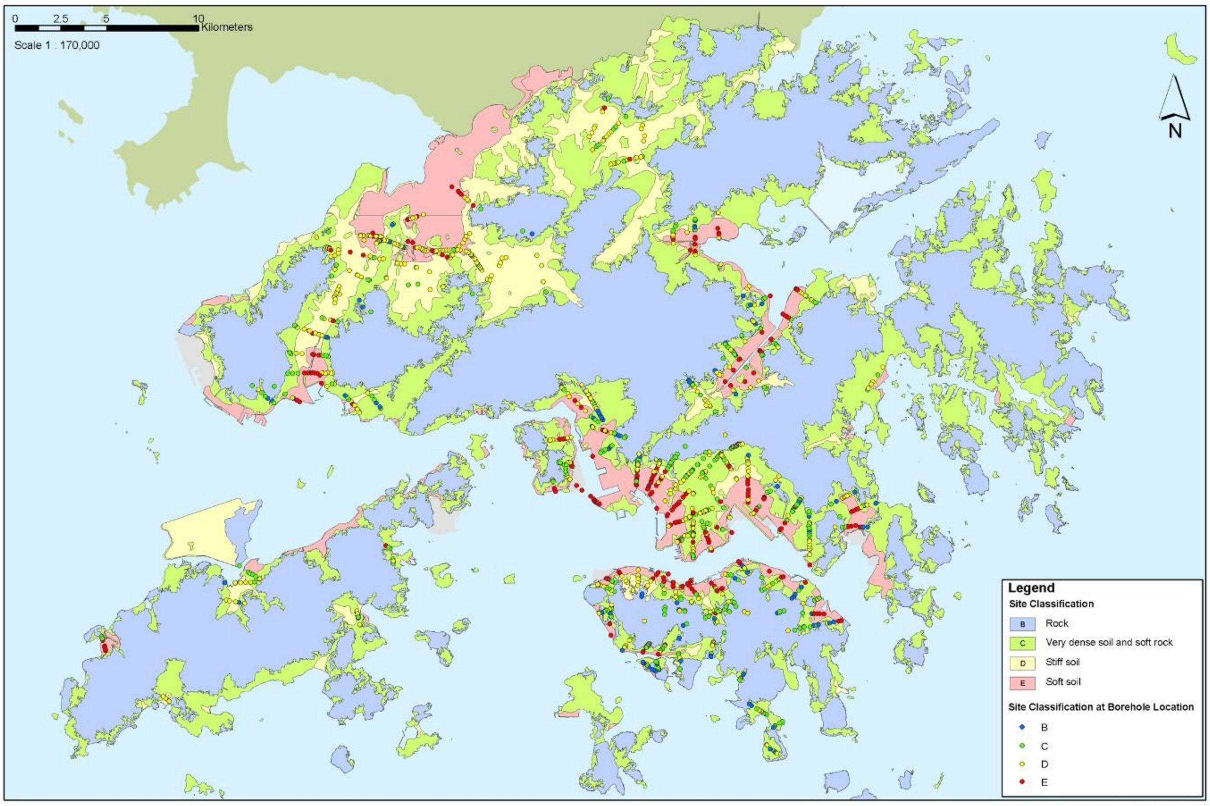


Figure 16: Soil class zoning map developed for the Hong Kong region

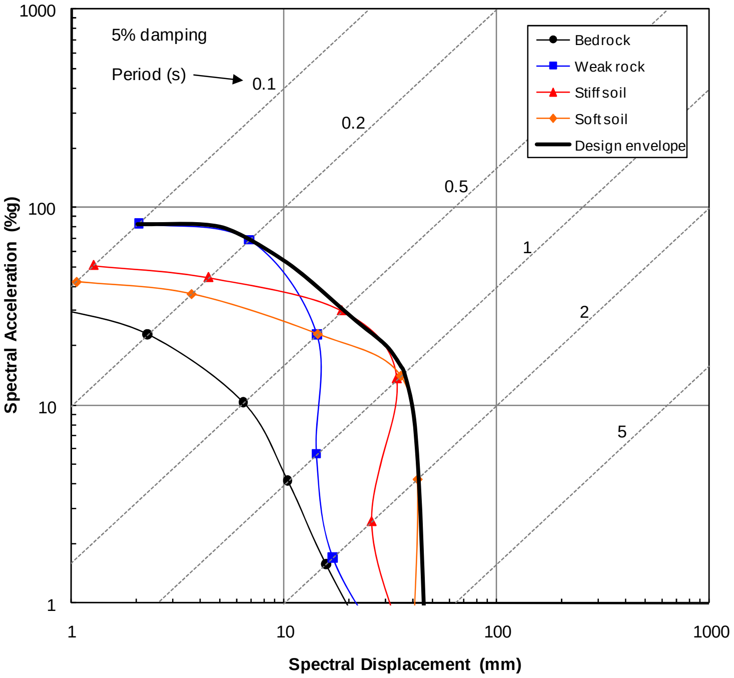


Figure 17: Demand spectra for the different soil classes in Hong Kong having a probability of 10% in the next 50 years

The HAZUS methodology gives typical capacity and fragility curves for low to medium rise buildings up to about 12 storeys. These values depend on the level of seismicity that the buildings are designed against which for Hong Kong is not considered. Hong Kong does have significant wind loading however and studies were carried out to determine the adjustments required because of this. Studies including linear and non-linear dynamic analyses were also carried out for a range of highrise buildings above 12 storeys to estimate the capacity and fragility curves for these.

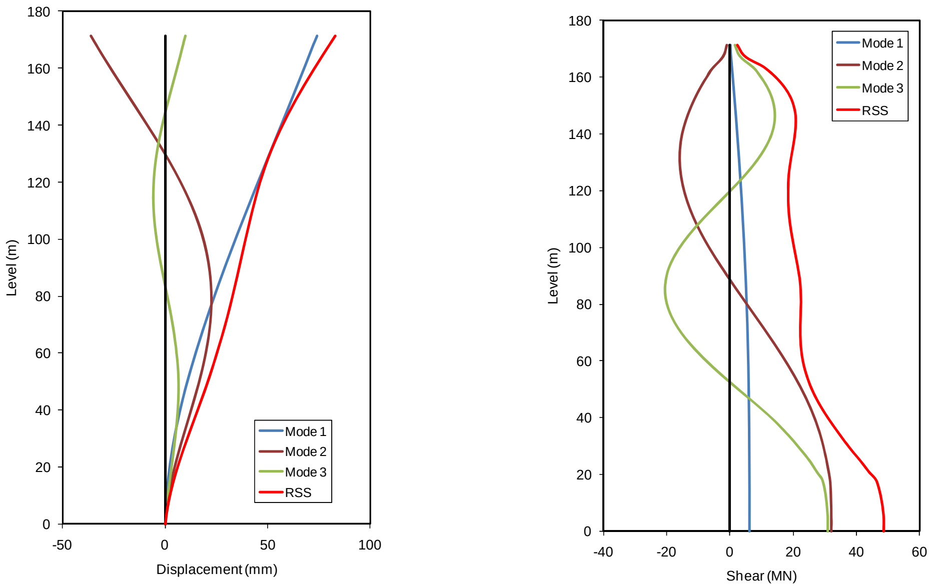


Figure 18: Linear dynamic response of a typical 40 storey shear wall building in Hong Kong

The results of a linear dynamic analysis of a typical 40 storey reinforced concrete shear wall building are shown in Figure 18. Interestingly while the displacement is controlled by the first mode response, the shear force is controlled by the second and third modes in each direction. This implies a significant dependence on higher mode effects and to some extent raises questions about the direct application of the HAZUS methodology for these high rise buildings. Given that high rise buildings over 15 storeys make up the majority of dwellings, commercial and industrial buildings in Hong Kong, this is an important consideration.

The study was completed by carrying out a GIS analysis of the region incorporating the distributions of the soil site classes as shown in Figure 16 together with the known layout of the buildings, their uses and their heights. Hong Kong has a particularly good building database and an extract is shown in Figure 19. The results showed that while medium and high rise buildings should behave well, low rise buildings are potentially at risk.

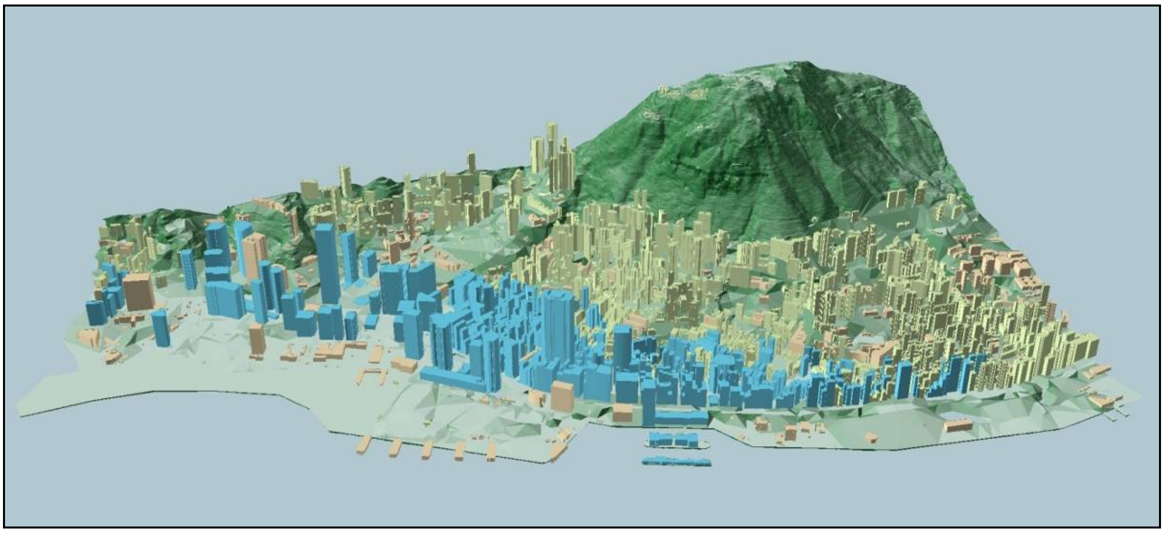


Figure 19: Extract of the Hong Kong building database (note the different colours refer to building use)

3.3 MALAY PENINSULA STUDY

This study was completed in 2008. It basically followed the approach used in the Hong Kong study but with the assessment of the building fragility functions for high rise buildings refined as described by Duan *et al*., 2008.

A major difference between Hong Kong and the Malay Peninsula is that the latter is affected by very large magnitude events at a distance of over 400 km. Figure 20, reproduced from the USGS website, clearly illustrates this with large magnitude earthquakes being mainly associated with the major subduction trench running along the south west side of Sumatra. There are also large events up to about magnitude 8 that occur along the Sumatra Fault shown on the figure. The presence of these large distant earthquakes gives rise to ground motion that contains significant energy at long structural periods as observed earlier by the bedrock records from the 1985 Mexico City earthquake shown in Figure 2. When these ground motions are amplified by soft ground conditions they can result in energy levels at longer periods that may warrant consideration in the design of taller buildings on soft soil sites. This is further discussed in the following section. It should also be noted that due to the significantly different spectral shape of soft soil sites on the Malay Peninsula to that of Hong Kong, structural analyses show that higher mode effects are not significant and a displacement based approach, as suggested by HAZUS, is more readily applicable.

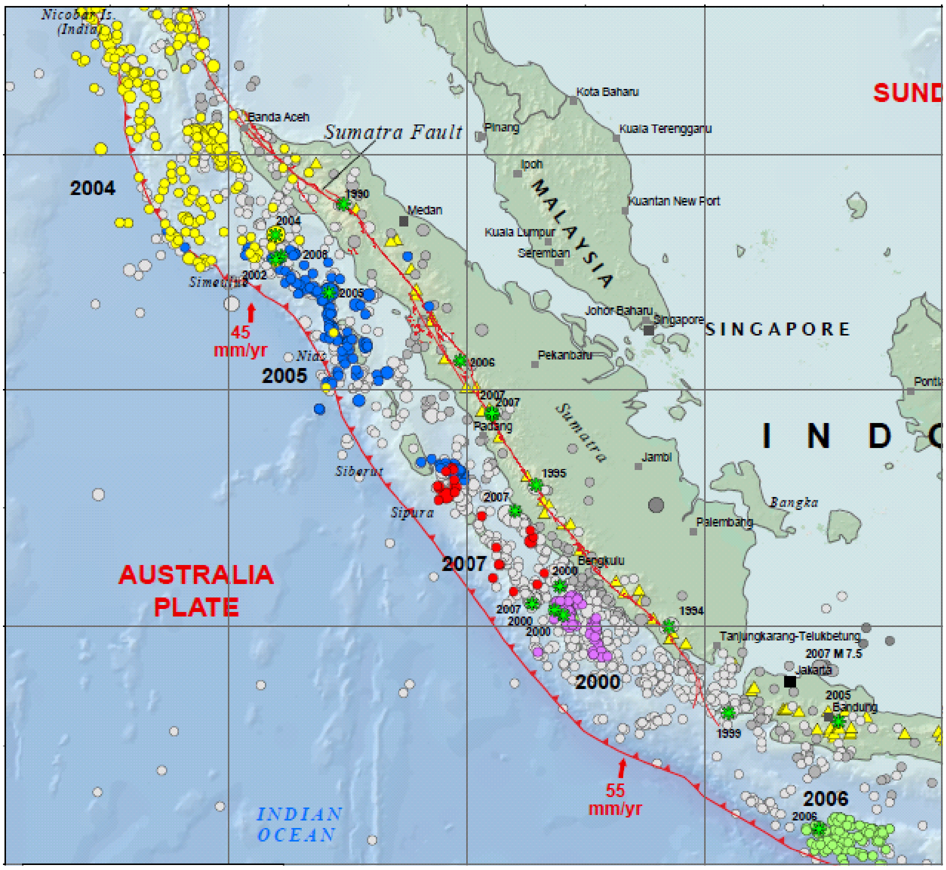


Figure 20: Earthquakes near to the Malaysian Peninsula

4 CONCLUSIONS

A comparison between the ground motions having a 10% probability of being exceeded in the next 50 years determined for soil conditions in the UK, Hong Kong and the Malay Peninsula are shown in Figure 21. The estimated maximum response spectrum for Newcastle and the measured Mexico City Lakebed spectrum are also shown. The US code value for San Francisco (ignoring very near fault effects) is also added for illustration of a design spectrum for a known high seismicity area. In addition the cut-off spectral value criterion implied by the current US design code (IBC, 2009) which defines the ground motion spectra above which seismic design of buildings is required is also shown. It can be seen that the UK spectrum is at about this cut-off level whereas Hong Kong is consistently above it except for buildings over 20 storeys high and the Malay Peninsula spectrum exceeds the criterion for buildings over about 8 storeys for soft soil sites.

The red arrow at 45 degrees is pointing in the direction of increasing spectral velocity and it is suggested that spectral velocity is a better indicator of damage potential than spectral acceleration or spectral displacement. This is because velocity is related to displacement over building period which is very closely related to inter-storey drift (displacement over building height) as building period is almost linearly related to building height. It is recommended that the spectral criterion for the consideration of seismic design for ordinary buildings be set at the constant velocity value suggested by the IBC. This corresponds to a spectral velocity value of 100mm/sec for a ground motion having a 10% probability of being exceeded in the next 50 years.

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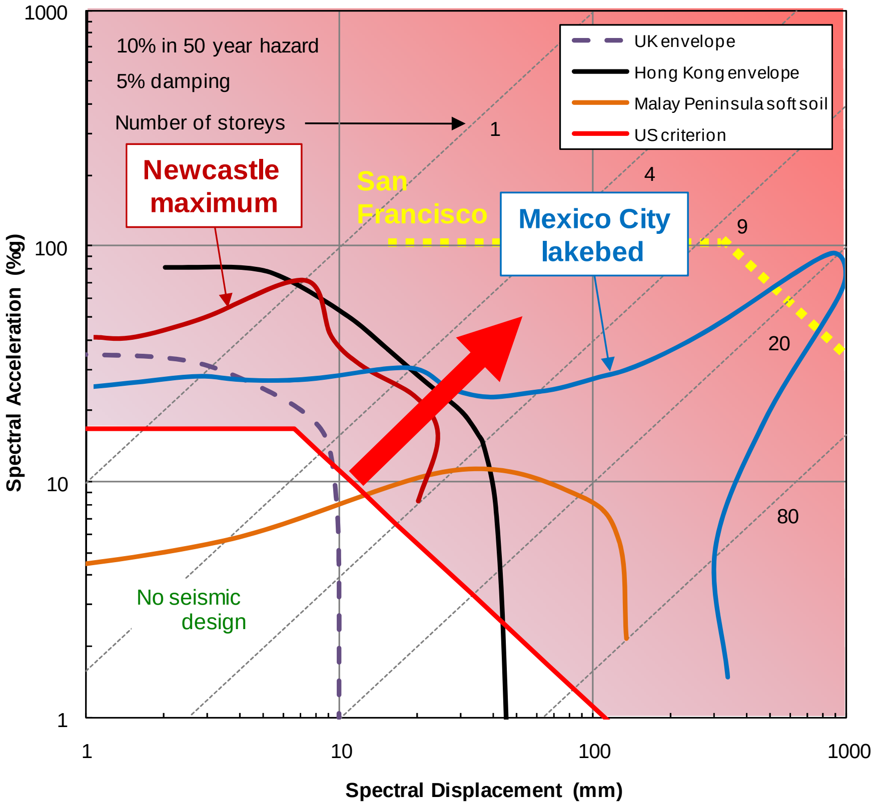

Figure 21: Demand spectra having 10% probability in the next 50 year for UK, Hong Kong and Malay Peninsula and San Francisco compared to the estimated 1989 Newcastle surface ground motion and measured at Mexico City in 1985.

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