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SYNOPSIS This paper examines the sensitivity of uniform hazard response spectra to the variability of the ground motion attenuation in areas of low to moderate seismicity. The variabilities of a number of published attenuation relationships are examined. Many of these relationships show that the standard deviation tends to increase as the natural period increases and some show a tendency for the standard deviation to reduce as the earthquake magnitude increases. These published works tend to be derived from earthquake data for areas of high seismicity and therefore the paper includes a critical review of what values of standard deviation are appropriate for regions of low to moderate seismicity.

INTRODUCTION

Seismic design of structures worldwide has made use of standard response spectral shapes anchored to peak (or effective) horizontal ground acceleration. These shapes have traditionally been derived for areas of high seismicity, for example California, where sufficient time histories have been recorded to enable a meaningful spectral shape to be derived statistically. Over recent years uniform hazard response spectra (UHRS) have been proposed as a rational alternative method of specifying design earthquake ground motions for design. The UHRS are generated using a probabilistic seismic hazard assessment methodology to produce a response spectrum such that all points on the spectrum have an equal probability of being exceeded within any given time period.

The UHRS considers the possibility of a range of earthquakes occurring in the vicinity of the site and includes the contributions of all these earthquakes. In areas of low to moderate seismicity the short period values of the UHRS are dominated by contributions from small nearby earthquakes whereas the long period values are dominated by more distant moderate to large earthquakes. It is also very clear that the spectral shape changes when moving from an area of high seismicity to an area of low seismicity with the UHRS in area of low seismicity showing a much lower ratio of long to short period motions.

VARIABILITY OF GROUND MOTION

A significant factor which controls the UHRS calculated using probabilistic methods is the variability of the attenuation relationship. Statistical analysis of observed ground motions shows the variability is log-normally distributed and can therefore be represented by a standard deviation of the logarithm of the spectral values. The higher the value of the standard deviation of this distribution (σ) used in the hazard analysis, the more chance there is that the hazard values will scatter to much higher levels than the predicted mean, which will have a significant effect on the calculated probabilistic hazard value.

Data on earthquake ground motions which can be used to study this variability has generally been obtained from areas of highly seismic plate boundary regions. Various attenuation relationships for response spectral values has been published in the last ten years. They are generally derived from fitting equations to data obtained from a particular region or tectonic setting. Relationships obtained in this way often include the standard deviation. Recently, in the USA in particular, stochastic models have been used to postulate theoretical attenuation relationships from a knowledge of stress drop, rock quality factor and energy release.

In contrast recent studies such as Dahle et al (1990) have attempted to study data from regions remote from plate boundaries and include a disparate set of earthquake records. Their relationship is based on 87 strong motion records from 56 different earthquakes in Italy, Greece, Yugoslavia, China, Australia, Germany, Canada, Eastern USA and Norway. The statistical derived variability from these studies is much larger than usual, reflecting difference in style of faulting and ground attenuation characteristics. Dahle et al (1990) include values of standard deviation of the natural logarithm response spectral values up to 1.01.

When compared with a range of published relationships, the Dahle et al (1990) standard deviation values appear high. For instance Ambraseys and Bommer (1991) examined peak acceleration values from 529 records of 219 shallow earthquakes in the European area, and hence derived a standard deviation of the natural logarithm (ln) of 0.6. Given their rigorous treatment of the data and the large number of records, it is unlikely that a standard deviation lower than this value is appropriate. In Eastern USA Algermissen and Leyendecker et al (1992) state that a standard deviation of ln of 0.76 is appropriate.

Other published relationships examined in this paper are: Joyner and Boore (1982) for rock sites in Western USA; Naumoski (1984) for rock and stiff soil sites in South and East Europe; Atkinson and Boore (1990) for hard rock sites in Eastern USA; Boore and Joyner (1991) for deep soil sites in Eastern USA; Sadigh et al (1987) for rock sites in Western USA; Idriss (1987) for rock sites in Western USA; and Principia Mechanica Ltd (PML) (1988) for hard sites in intraplate regions appropriate for use in the UK.

Figure 1 shows the variation of σ with natural frequency for all the attenuation laws used in this paper. This figure shows that in all cases the standard deviation is seen to reduce with increasing natural frequency. As previously stated it is seen that the Dahle et al (1990) data is consistently higher than the other relationships. If the Sadigh et al (1987), Idriss (1987) and Dahle et al (1990) data are ignored then a relatively consistent set of data is observed reducing from about 0.8 at 0.2Hz to about 0.6 at 100Hz. Therefore, it is suggested that the values of standard deviation plotted on Figure 1 are used with the Dahle et al (1990) attenuation law.

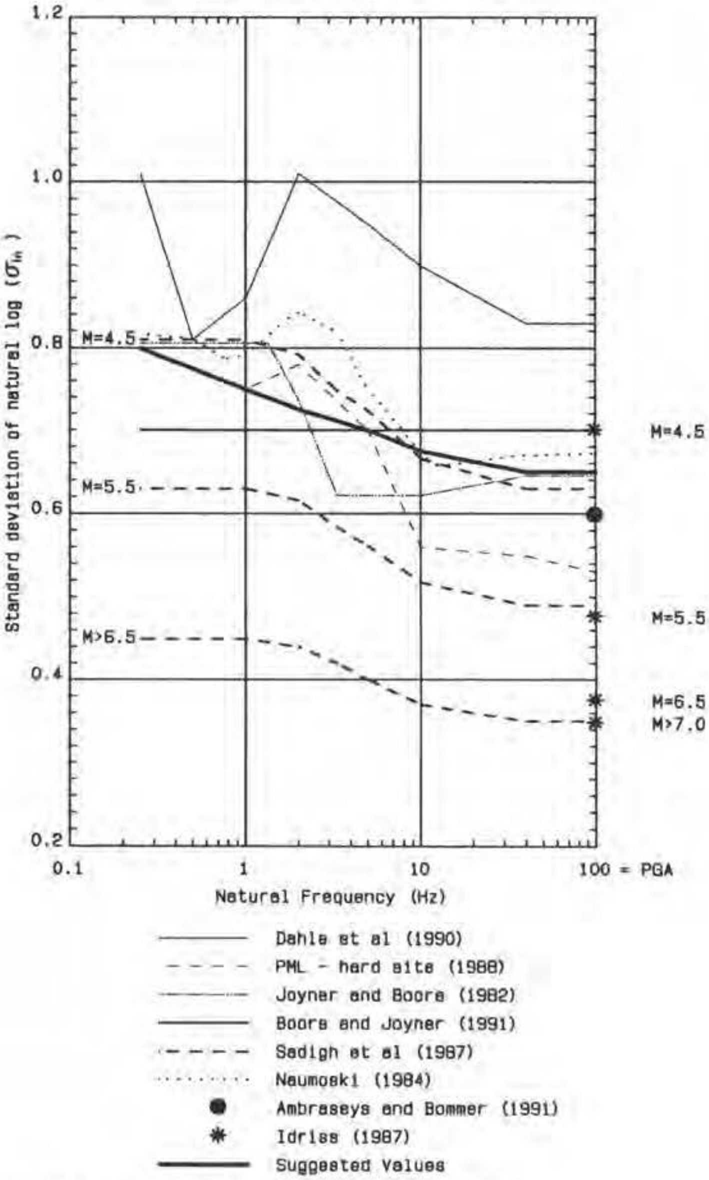


FIGURE 1 Variation of Published Sigma Values

The Sadigh et al (1987) and Idriss (1987) relationships have magnitude dependent values of standard deviation. They indicate that as the magnitude increases the standard deviation reduces. If the magnitude dependent Sadigh data were to be used for the UK, σ would be determined by the low magnitude values ($M \leq 4.5$) for high frequencies and the medium magnitude ($M=5.5$) for the lower frequencies indicating that perhaps a constant value of σ of about 0.64 may be appropriate for all frequencies.

ANALYSIS OF VARIABILITIES

For the study presented in this paper the variation with natural frequency and magnitude was examined by calculating the UHRS for a probability of exceedence of $1x10^{-4}$ using the Oasys program SISMIC. This program uses the method proposed by Cornell (1968) to numerically determine the probability of a given hazard value. It also uses the logic tree methodology (Coppersmith and Youngs, 1986) to incorporate various input parameters with their associated weighting and keeps a record of the contribution of each earthquake magnitude and distance. The base seismic data was taken from the Ove Arup and Partners (1993) study of UK seismic hazard and risk for the Department of the Environment and is shown in Figure 2.

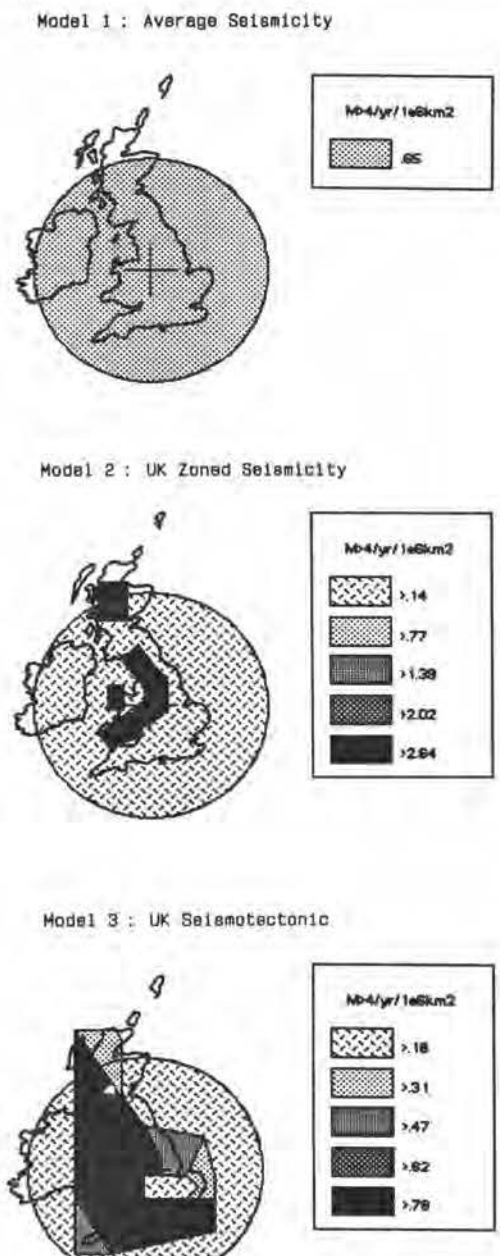


FIGURE 2 Geometry of Source Models

Variation of σ with natural frequency UHRS were calculated at one site in the UK. The location of this site is in an area of higher than average seismicity as shown in Figure 2. The following input parameters were used: Dahle et al (1990) attenuation relationship; M_{min} of 4.0; M_{max} of 6.5; depth distribution as shown in Table 1.

TABLE 1 Depth Distribution

Hypocentral Depth (km)	Weight
3 to 7	0.4
7 to 12	0.4
>12	0.2

Three runs have been carried out to examine the effect of the standard deviation varying with natural frequency;

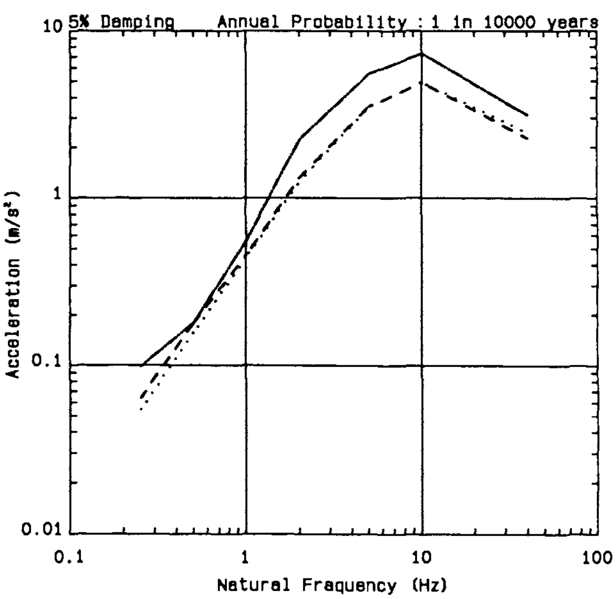
TABLE 2 Variation of σ with Natural Frequency

Run	σ value
1	derived by Dahle et al (1990),
2	proposed in Figure 1,
3	constant of 0.7

Two additional runs have been analysed to examine the effect of the standard deviation varying with magnitude;

TABLE 3 Variation of σ with Magnitude

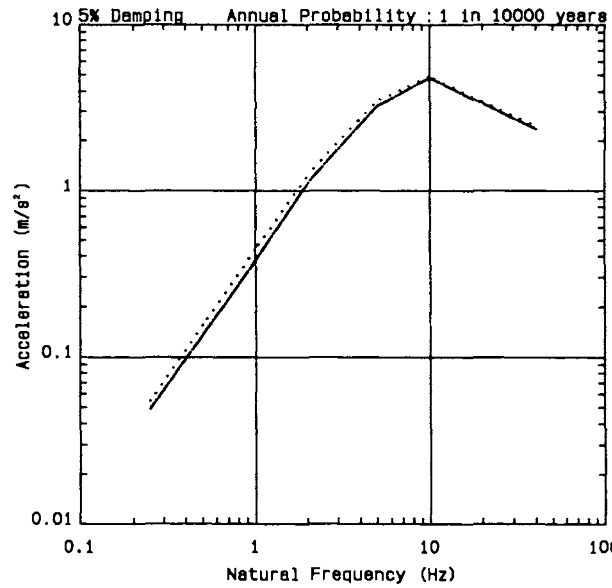
Run	σ value
4	Run 3 but varying with magnitude
5	Run 2 and varying with magnitude



1 ———— Sigma Proposed by Dahle et al (1990)
2 - - - - Frequency Dependent Sigma Proposed in Figure 1
3 ········ Constant Sigma of 0.7

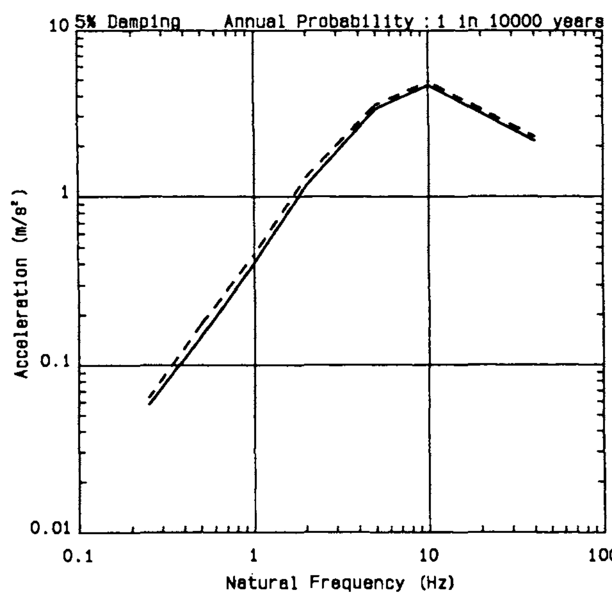
FIGURE 3 Effect of Sigma Variation with Frequency on UHRS Shape

For both these runs the σ values were assumed to reduce by 0.16 units at the peak ground acceleration for each unit increase in magnitude.



3 ········ Constant Sigma of 0.7
4 ———— Sigma Varying with Magnitude Only

FIGURE 4 Effect of Sigma Variation with Magnitude on UHRS Shape



2 - - - - Sigma Varying with Frequency Only
5 ———— Sigma Varying with Magnitude and Frequency

FIGURE 5 Effect of Sigma Variation with Magnitude and Frequency on UHRS Shape

DISCUSSION OF RESULTS

The UHRS calculated by the first three runs are shown in Figures 3. The difference between run 1 and 2 shows the significant reduction in hazard due to the use of lower standard deviation values. The difference between run 3 and 2 shows the modest effect of the varying standard deviation values with natural frequency.

The UHRS resulting from runs 3 and 4 are compared in Figure 4. They show the effect of σ varying with magnitude alone is small. The results of runs 2 and 5 are compared on Figure 5. As can be seen on this figure the effect of adding magnitude variance onto frequency variance is to reduce the hazard level. This is not surprising as the σ values used consistently reduce with increasing magnitude.

The effect on magnitude contribution to the UHRS for natural frequencies of 1 and 10Hz are shown in Figure 6. The figure shows the magnitude contribution for constant σ values (run 3), σ varying with frequency only (run 2), σ varying magnitude only (run 4) and σ varying with both magnitude and frequency (run 5). As expected the magnitude contribution for 10Hz is mainly due to low magnitude events, whilst for 1Hz the contribution is greater at higher magnitudes. Runs 4 and 5 (magnitude variation of σ) also show a greater contribution from low magnitude events compared to runs 2 and 3.

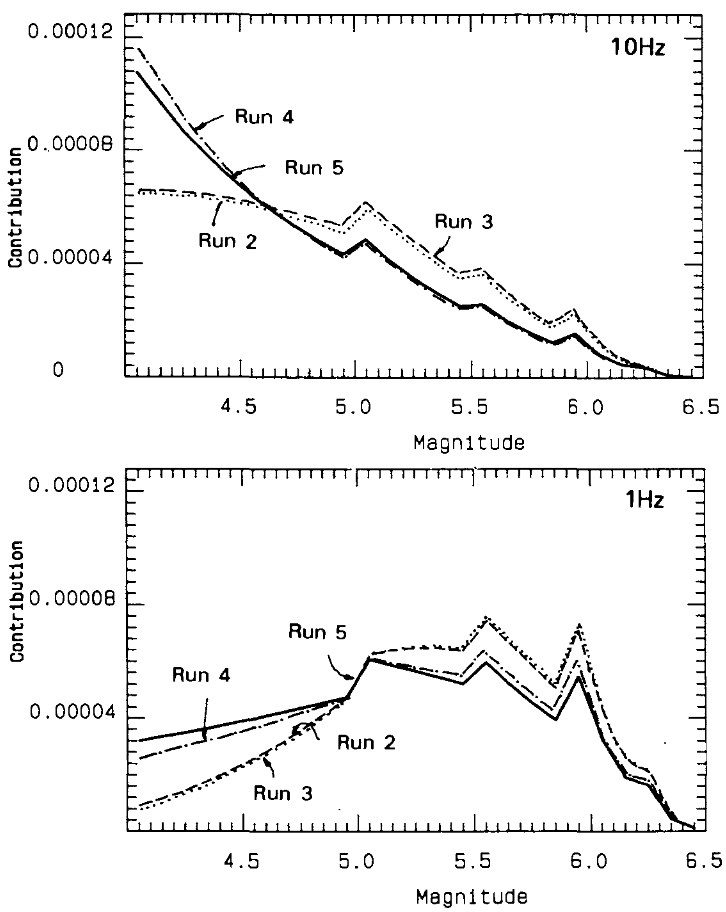


FIGURE 6 Effect of Variation of Sigma for Magnitude Contribution

CONCLUSIONS

- The effect of σ value varying with natural frequency is to increase the hazard level at low natural frequencies.
- The effect of σ value varying with magnitude is to slightly reduce the hazard level at all natural frequencies.
- When a σ value which varies with magnitude is used, there is a greater contribution to the hazard from low magnitude events.

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