DISTRIBUTION OF SCATTER IN NEW ZEALAND ACCELEROGRAPH DATA

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ABSTRACT

This study examines the currently available set of 22 New Zealand strong motion accelerograms to determine values of the scatter parameters for use in correcting for attenuation uncertainty in seismic hazard analyses. In particular, scatter of observed acceleration response spectral ordinates about mean values predicted by the attenuation law of Katayama, Iwaski and Seaki is investigated. It is found that to a high level of statistical significance, the observed spectral ordinates are lognormally distributed about predicted values. For the data as a whole, lumping samples from the nine natural periods studied, the standard deviation of the logarithmic residuals is $\sigma_{10} = 0.25$. However, values of σ_{10} for distinct natural periods are quite scattered in an apparently random manner, suggesting that the set of accelerograms is not large enough to yield stable results on a period-by-period basis. Furthermore, since there is no recording of severely damaging ground motions amongst the accelerograms, it is not clear that the value of $\sigma_{10} = 0.25$ is characteristic of hazardous ground motions in New Zealand, especially when it is compared with the value of 0.3 obtained from the more extensive Japanese data set. For immediate practical purposes, it is proposed that scatter parameters obtained from a combined New Zealand-Japanese data set be used. These records taken together yield values of σ_{10} increasing from 0.28 at a natural period of 0.1 s to 0.32 at 1.0 seconds and above. Employing these values rather than $\sigma_{10} = 0.25$, results in a 20 percent increase in the peak of the 150-year uniform risk spectrum for Wellington.

INTRODUCTION

During the past five or six years a number of studies have been made of seismic hazard in New Zealand using probabilistic seismic hazard analysis techniques[1-4]. These studies have been employed to derive the uniform risk response spectra used in the draft NZNSEE code "Seismic Design of Bridges"[5,6] and, with some refinement, are being used to develop spectra for the forthcoming revision of the NZ loadings code for buildings, NZS 4203. Of the various sources of uncertainty in the estimation of seismic hazard, one of the most critical is uncertainty in the attenuation law[7-9]. The computed seismic hazard is highly sensitive to the degree of randomness in attenuation. Therefore it is important that the random component of the attenuation law be quantified as precisely as possible according to the characteristics of the region under consideration. If the degree of dispersion of attenuation about the mean attenuation law is ignored or underestimated, then the hazard may be seriously underestimated. On the other hand, comparatively small amounts of conservatism in the dispersion parameters may result in large increases in computed hazard. Precise estimation of the appropriate degree of randomness is especially difficult for New Zealand because of the scarcity of strong motion data.

The aim of this article is to examine the set of New Zealand strong motion accelerograms in order to find appropriate values of the attenuation uncertainty or randomness parameters with respect to the attenuation law of Katayama, Iwasaki and Seaki[11] used in current hazard analyses[10] in this country. The companion article[10] in this issue outlines the hazard analysis procedure, and reviews recent work in the application of hazard analyses to New Zealand and in the formulation of seismic design loads. The reader unfamiliar with seismic hazard analyses is referred to that article, especially to the discussion of attenuation uncertainty.

The point of departure of the present article is equation (11) of the companion article, namely:

$$\hat{i} = Z \, i(m,r) \qquad (1)$$

in which m denotes earthquake magnitude, r distance and $\hat{i}$ denotes the (random) intensity of motion produced at a site at a distance r by an earthquake of magnitude m. The function $i(m,r)$ denotes the mean attenuation law; Z is a random variable describing randomness in attenuation. Note that equation (1) models the earthquake source, through its dependence on m, as well as the attenuation of seismic waves with distance.

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No	Accelerograph Site	Earthquake	Date	Magnitude	Epicentral Distance km	Ground Condition
1	Westport Telephone Exchange	Inangahua aftershock	24/05/68	6.0	35	II
2	Westport Telephone Exchange	Inangahua aftershock	25/05/68	5.5	25	II
3	Westport Telephone Exchange	Inangahua aftershock	14/06/68	5.5	30	II
4	Te Anau Fire Station	Milford Sound	04/05/76	7.0	84	III
5	Milford Sound Hotel	Milford Sound	04/05/76	7.0	37	III
6	Wanaka National Park Headquarters	Milford Sound	04/05/76	7.0	134	III
7	Vogel Building Wellington (Remote)	Cook Strait	18/01/77	6.2	64	II
8	Vogel Building Well'ton (Basement)	Cook Strait	18/01/77	6.2	64	II
9	Wellington Airport Fire Station	Cook Strait	18/01/77	6.2	63	II
10	Gray and Elliot Bdg Bute St, Wellington	Cook Strait	10/01/77	6.2	64	III
11	Central Library Wellington	Cook Strait	10/01/77	6.2	65	IV
12	ANZ Bank, Cuba St Wellington	Cook Strait	10/01/77	6.2	65	III
13	Gear Meat Co. Petone	Cook Strait	10/01/77	6.2	76	III
14	PEL Bdg, DSIR Lower Hutt	Cook Strait	10/01/77	6.2	77	III
15	PEL Bdg, DSIR Lower Hutt	Seddon	23/04/66	6.0	63	III
16	Napier Telephone Exchange, Marewa	Napier	05/10/80	5.6	24	IV
17	Napier Telephone Exchange, Marewa	?	02/09/82	5.4	35	IV
18	Ooanui Gas Plant	?	16/04/83	5.5	42	IV
19	Ooanui Gas Plant	?	16/04/83	5.2	39	IV
20	Haywards NZE Distribution Station	Palliser Bay	01/11/68	5.5	50	I
21	Chief Post Office Gisborne (Ground floor)	Gisborne	03/03/82	5.1	25	IV
22	Chief Post Office Gisborne (car park)	Gisborne	03/03/82	5.1	25	IV

Table 1. Ground-level recordings from crustal earthquakes in New Zealand.

Our problem is to determine the distribution of Z for New Zealand strong motion, given that the mean attenuation $i(m,r)$ is represented by the model of Katayama, Iwasaki and Seaki[11]. At the time of writing 22 New Zealand strong motion accelerograms were available, and observed values of Z derived from them form the basic data set. First, the common assumption that Z is lognormally distributed is examined, and then means and standard deviations are estimated.

NEW ZEALAND STRONG MOTION ACCELEROGRAMS

Twenty-two strong motion accelerograms recorded by the Engineering Seismology section of the New Zealand DSIR at ground level, on basement floors or in the free field form the basis for the study described below. The accelerograms are listed in Table 1, together with seismological and site information. Their geographical distribution is shown in Figure 1. The 22 accelerograms come from 11 earthquakes, three of which were aftershocks. Records 1 to 16 formed the set studied earlier by Mulholland[3]; numbers 17 to 22 have been processed since Mulholland's study.
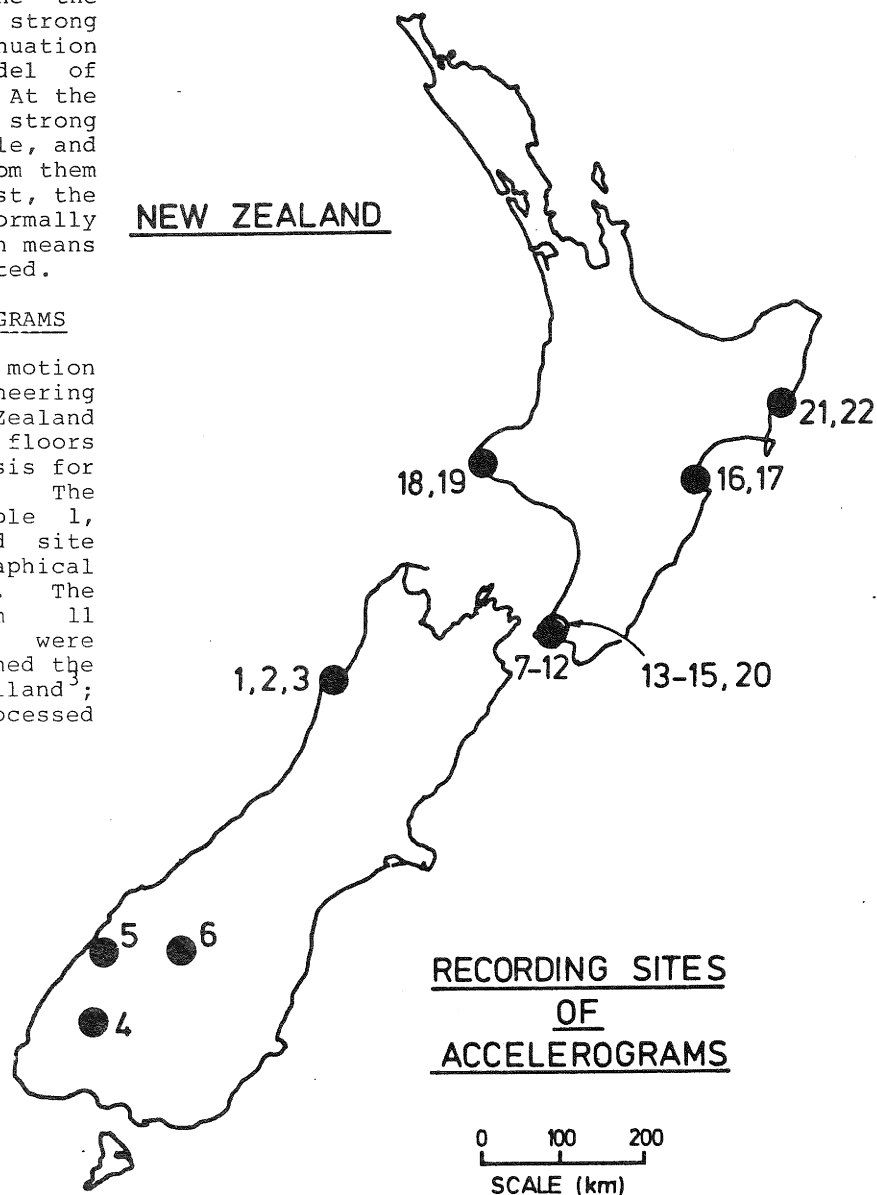

Figure 1. Recording sites of the 22 accelerograms of the data set

The ground conditions at the accelerograph sites are classified according to the four-step Japanese system[13] employed by Katayama et al.[11], using borelog data where possible. In some cases the classifications assigned by Mulholland have been revised (resulting in a small reduction in scatter). Table 2, from Ohashi et al.[12], gives details of the Japanese site classification system, and has been used in the reclassification of the New Zealand sites.

Table 2.   Japanese system for
classifying site ground
conditions (from ref. 12)

Group	Definitions[1]
I	(1) Ground of the Tertiary era or older (defined as bed rock hereafter) (2) Diluvial layer[2] with depth less than 10 metres above bedrock
II	(1) Diluvial layer[2] with depth greater than 10 metres above bedrock (2) Alluvial layer[3] with depth less than 10 metres above bedrock
III	Alluvial layer[3] with depth less than 25 metres, which has soft layer[4] with depth less than 5 metres
IV	Other than the above

(Notes)   1) Since these definitions are not very comprehensive, the classification of ground conditions shall be made with adequate consideration of the [bridge] site.

Depth of layer indicated here shall be measured from the actual ground surface.

2) Diluvial layer implies a dense alluvial layer such as a dense sandy layer, gravel layer or cobble layer.

3) Alluvial layer implies a new sedimentary layer made by a landslide.

4) Soft layer is defined in Section 3.7 [of reference 13] "Soil Layer Whose Bearing Capacities are Neglected in Earthquake Resistant Design".

SCATTER ABOUT THE ATTENUATION MODEL OF KATAYAMA ET AL.

A set of observed values of Z was obtained by first computing the absolute acceleration response spectrum with five percent damping for each of the 22 accelerograms. These spectra were then sampled at nine natural periods T_j in the band 0.10 s to 2.0 s to obtain a set of observed spectral ordinates $\hat{S}_{ij}$ (i = 1, 22; j = 1, 9). Values of $\hat{z}_{ij}$ were computed by dividing the observed spectral ordinates $\hat{S}_{ij}$ by the corresponding values S_{ij} predicted by the Katayama model. That is,

$$z_{ij} = \frac{\hat{S}_{ij}}{S_{ij}(m_i, r_i, GC_i)} \qquad (2)$$

where m_i, r_i, GC_i are the magnitude, epicentral distance and ground condition of the ith accelerogram, taken from Table 1. Noting that the various influences on strength of shaking (such as the earthquake source mechanism, directivity effects, properties of the propagation path and local site conditions) are multiplicative, and appealing to the central limit theorem of probability theory, it is expected that Z will be lognormally distributed. Thus the set of logarithmic residuals

$$x_{ij} = \log_{10} z_{ij} \qquad (3)$$

were taken as the basic data set for this study. These residuals are listed in Table 3, together with means and standard deviations of various subsets.

First, the set of logarithmic residuals is plotted in Figure 2 against the independent variables of the Katayama model to check for any obvious trends. There does not appear to be any gross trend with respect to distance or magnitude, although in both cases there appears to be a slight overall decrease in the mean value of X with both increasing distance and magnitude. However the trend is slight, especially in view of the amount of scatter overall, and is due principally in both figures to data from a single earthquake, the 1976, M = 7 Milford Sound earthquake. As for the amount of scatter, there does not appear to be any obvious correlation with either distance or magnitude. In the plot of X versus ground condition, the average value of X appears to be smaller for Class 3 than for the other categories, although again the amounts of scatter seem similar in all cases. The other unusual group in the ground condition plot is that of GC = 1. However, with only one recording in this category (Haywards, 1968), little general significance can be attached to it. In the plot of X versus T there is a small decrease in the mean value of X with increasing period (as observed by Mulholland[4]) but here again, the amount of scatter appears to be independent of T.

To examine the distribution of the residuals in more detail, and in particular to test the assumption that Z is lognormally distributed, histograms of observed values of X are plotted in Figure 3 for the periods T = 0.1, 0.5, 1.0 and 2.0 s. Corresponding normal distributions are also shown. There are not enough data in these plots to apply the Chi-Squared goodness-of-fit test at the individual periods (a minimum of five samples per category is required[14]). However, the Kolmogorov-Smirnov ($K_{T}S$) test (see, for example Ang and Tang[15]) may be employed. Under this test, the worst case occurs in the T = 1.0 s data, for which the cumulative distribution is plotted in Figure 4. The greatest

		NATURAL PERIOD, Sec		
		0.10	0.20	0.30	0.40	0.50	0.70	1.00	1.50	2.00	Mean	Std Dev
WESTPORT TEL EXCH	25/05/68											
	N10W	0.479	0.045	0.006	-0.165	-0.204	-0.062	-0.276	-0.219	-0.330	-0.081	0.245
	S80W	0.464	0.308	0.103	-0.156	-0.250	-0.213	-0.158	-0.279	-0.373	-0.062	0.287
WESTPORT TEL EXCH	24/05/68											
	N10W	-0.043	-0.338	-0.180	0.048	-0.055	0.037	-0.044	0.240	0.127	-0.023	0.168
	S80W	-0.078	0.185	-0.128	-0.138	0.015	-0.010	-0.131	0.025	-0.035	-0.033	0.103
WESTPORT TEL EXCH	14/06/68											
	N10W	0.611	0.037	-0.207	-0.341	-0.362	-0.257	-0.115	-0.228	0.025	-0.093	0.300
	S80W	0.397	-0.060	0.125	0.040	-0.030	-0.111	-0.161	-0.241	-0.065	-0.012	0.187
TE ANAU FIRE STN	04/05/76											
	N39W	-0.348	-0.540	-0.361	-0.471	-0.413	-0.301	-0.348	-0.009	-0.003	-0.310	0.187
	S51W	-0.446	-0.666	-0.572	-0.469	-0.505	-0.261	-0.318	-0.035	0.123	-0.350	0.257
MILFORD SOUND	04/05/76											
	S41E	-0.125	-0.380	-0.160	-0.156	0.091	-0.218	-0.044	-0.266	-0.426	-0.187	0.160
	N49E	-0.186	-0.419	-0.186	-0.034	0.033	-0.214	-0.267	-0.329	-0.274	-0.208	0.140
WANAKA NAT PARK HQ	04/05/76											
	S07W	-0.215	-0.233	-0.366	-0.365	-0.426	-0.021	-0.211	0.283	0.022	-0.170	0.227
	S83E	-0.177	-0.261	-0.287	-0.298	-0.240	-0.013	0.124	0.189	0.110	-0.095	0.197
VOGEL BDG WN (A)	18/01/77											
	N02E	0.214	0.236	0.207	0.264	0.329	0.362	-0.024	-0.018	-0.042	0.170	0.157
	N88W	0.241	0.325	0.432	0.368	0.416	0.451	0.063	-0.198	-0.058	0.227	0.236
VOGEL BDG WN (B)	18/01/77											
	S02W	-0.069	0.079	0.279	0.157	0.283	0.321	0.003	0.089	0.039	0.131	0.137
	S88E	-0.071	0.018	0.138	0.109	0.269	0.268	0.093	-0.072	-0.084	0.074	0.138
WELLINGTON AIRPORT	18/01/77											
	040	0.176	0.136	-0.022	-0.111	0.038	0.180	-0.073	-0.186	-0.352	-0.024	0.179
	130	0.200	-0.061	0.075	-0.186	-0.140	0.222	-0.250	-0.425	-0.283	-0.094	0.223
GRAY AND ELLIOT WN	18/01/77											
	040	0.032	0.282	0.247	0.071	0.273	0.058	-0.373	-0.513	-0.546	-0.052	0.336
	130	0.080	0.346	0.089	0.092	0.001	-0.085	-0.253	-0.561	-0.492	-0.087	0.296
PEL LOWER HUTT	18/01/77											
	040	0.142	0.152	0.326	0.524	0.144	-0.110	-0.511	-0.476	-0.571	-0.042	0.396
	130	-0.030	0.213	0.161	0.026	0.102	-0.163	-0.572	-0.705	-0.520	-0.165	0.346
WN CITY LIBRARY	18/01/77											
	040	-0.079	0.208	0.334	0.270	0.077	-0.172	-0.300	-0.487	-0.436	-0.065	0.306
	130	0.040	0.169	-0.013	-0.044	-0.164	-0.299	-0.438	-0.471	-0.404	-0.180	0.233
ANZ BK CUBA ST WN	18/01/77											
	040	-0.150	0.055	-0.048	-0.025	-0.193	0.045	-0.136	-0.369	-0.487	-0.145	0.184
	130	-0.109	0.084	0.111	0.071	0.077	0.011	-0.324	-0.442	-0.440	-0.107	0.233
PEL LOWER HUTT	23/04/66											
	050	-0.114	0.045	0.191	0.169	0.221	-0.035	-0.344	-0.311	-0.187	-0.041	0.214
	140	-0.245	-0.025	0.001	-0.323	-0.052	-0.100	-0.520	-0.688	-0.632	-0.297	0.269
GEAR MEAT PETONE	18/01/77											
	040	-0.148	-0.068	-0.035	-0.133	0.033	0.142	-0.033	-0.287	-0.126	-0.073	0.122
	130	-0.153	-0.156	-0.346	-0.136	0.154	0.160	-0.105	0.031	0.133	-0.046	0.175
NAPIER TEL EXCH	05/10/80											
	N25E	0.319	0.345	0.505	0.287	-0.026	-0.065	0.000	0.331	0.243	0.215	0.198
	N65W	0.256	0.409	0.348	0.172	0.252	0.156	0.112	0.376	0.330	0.268	0.105
NAPIER TEL EXCH	02/09/82											
	N25E	0.151	0.364	0.169	0.041	0.031	-0.050	0.097	0.087	0.081	0.108	0.116
	N65W	0.174	0.189	0.267	0.165	0.048	-0.258	-0.085	0.018	0.012	0.059	0.162
OOANUI GAS PLANT	16/04/83											
	N25W	0.249	0.247	0.417	0.363	0.251	0.039	-0.119	-0.124	-0.090	0.137	0.213
	S65W	0.082	0.194	0.273	0.166	0.058	-0.193	-0.322	-0.401	-0.303	-0.050	0.255
OOANUI GAS PLANT	16/04/83											
	N25W	0.334	0.370	0.362	0.185	0.138	-0.031	-0.080	-0.270	-0.256	0.084	0.254
	S65W	0.176	0.348	0.246	0.070	0.012	-0.097	-0.231	-0.016	-0.135	0.042	0.188
HAYWARDS DISTN STN	01/11/68											
	S05E	0.118	0.073	0.599	0.329	0.222	0.074	-0.099	0.042	-0.018	0.149	0.210
	N85E	-0.073	-0.131	0.157	0.205	0.155	0.187	0.120	0.083	-0.110	0.066	0.133
GISBORNE CPO (B)	03/03/82											
	S46E	-0.245	-0.051	0.072	-0.019	0.191	0.204	0.232	0.094	0.005	0.054	0.151
	N44E	-0.289	-0.115	-0.012	-0.089	0.117	0.260	0.652	0.163	0.037	0.080	0.269
GISBORNE CPO (A)	03/03/82											
	N46W	0.000	0.214	0.293	-0.011	0.228	0.361	0.329	0.052	-0.115	0.150	0.171
	S44W	0.023	0.184	0.141	-0.126	0.201	0.378	0.726	0.196	0.003	0.192	0.247
	MEAN	0.036	0.054	0.085	0.009	0.032	0.013	-0.107	-0.144	-0.157	-0.020	
	S	0.233	0.255	0.253	0.227	0.213	0.202	0.266	0.276	0.239		0.254

Table 3.   Observed values of logrithmic residuals for the 22 New
Zealand accelerograms with respect to the attenuation law
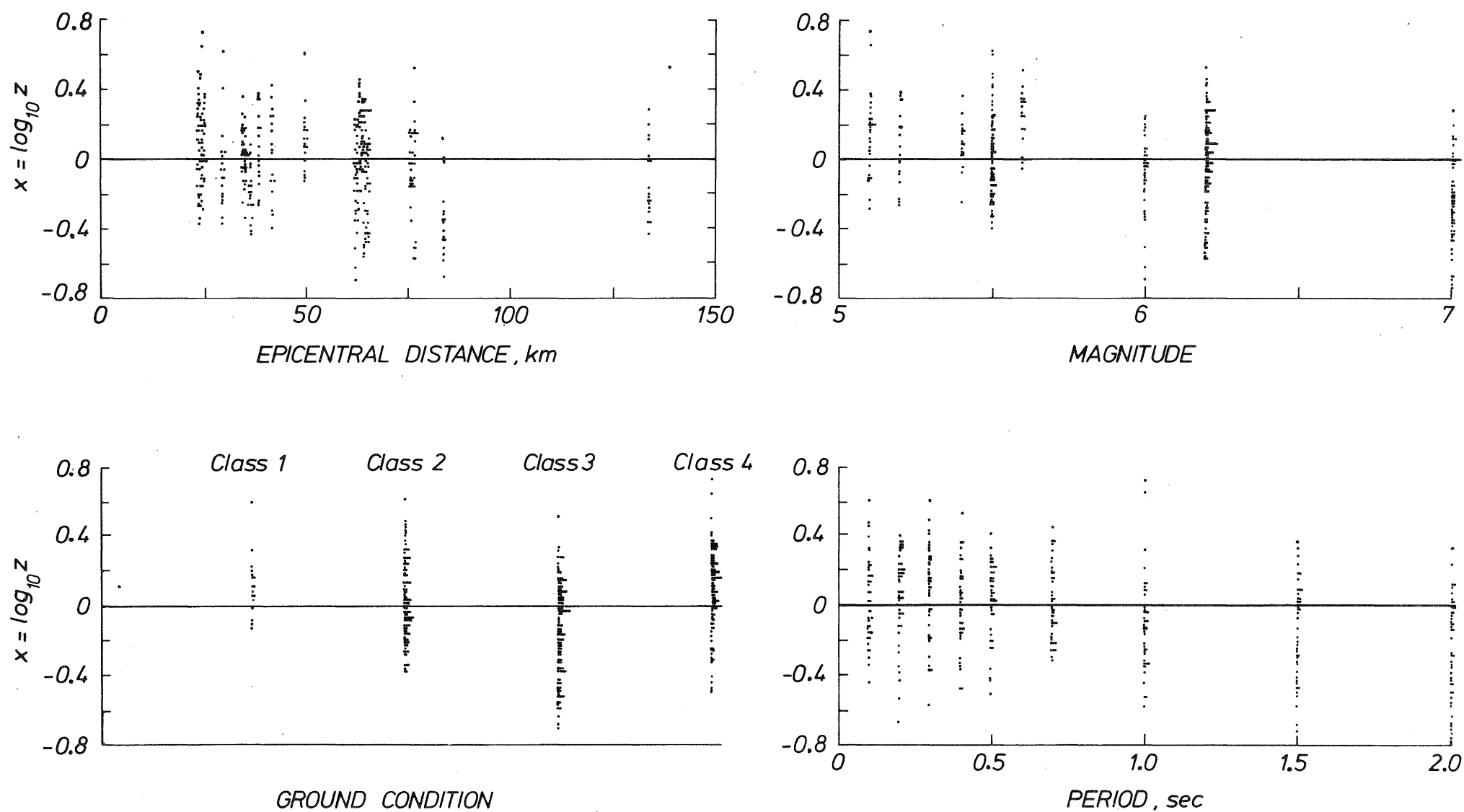of Katayama, Iwasaki and Seaki.

Figure 2. Plots of the logarithmic residuals versus the parameters of the Katayama attenuation law.

deviation, D_{max}, of the observed cumulative distribution from the fitted lognormal function is $D_{max} = 0.112$, well within the critical values of 0.20 and 0.16 at five percent and 20 percent confidence levels respectively, supporting the assumption that Z is lognormally distributed. Values of D_{max} found for other sampling periods are shown in Table 4. Also shown in the table are values of D_{max} assuming Z is normally distributed. As expected, it is seen that at most periods the lognormal assumption gives a markedly better fit. The overall fit is tested by lumping all nine period categories together. In this case $D_{max} = 0.0345$ when Z is assumed to be lognormal, and $D_{max} = 0.109$ assuming Z is normally distributed. Clearly the assumption of lognormality gives a much better fit overall.

When data at the four periods studied in Figure 3 are lumped together, the histogram shown in Figure 5 results. Clearly, these data fit the lognormal distribution well (suggesting that the samples at individual natural periods are too small). Lumping data for $x > 0.35$ and $x < -0.45$ to satisfy the $n > 5$ criterion, results in a chi-squared value of 4.80. This compares with a critical value of 15.5 at the five percent level, again strongly supporting the lognormal assumption.

Table 4. Values of D_{max} for the Kolmogorov-Smirnov test under the assumptions that Z is normally and lognormally distributed

Period, T sec	0.1	0.2	0.3	0.4	0.5	0.7	1.0	1.5	2.0
D_{max}, Z lognormal	0.106	0.087	0.070	0.048	0.101	0.091	0.112	0.085	0.105
D_{max}, Z normal	0.152	0.081	0.107	0.127	0.068	0.165	0.267	0.157	0.109

$T = 0.10$ s
$\bar{x} = 0.036$
$s = 0.233$

$T = 1.0$ s
$\bar{x} = -0.107$
$s = 0.266$

$T = 0.50$ s
$\bar{x} = 0.032$
$s = 0.213$
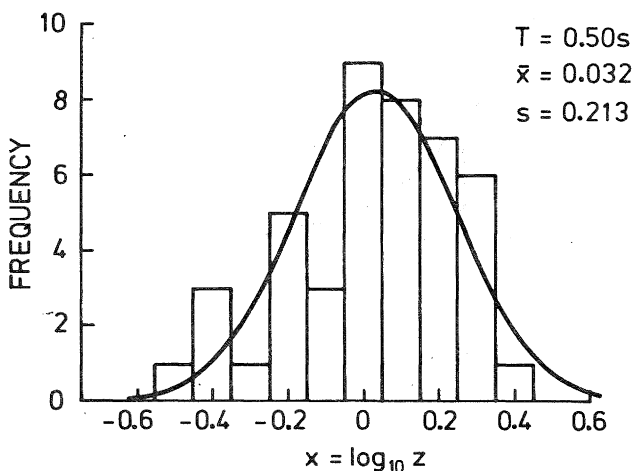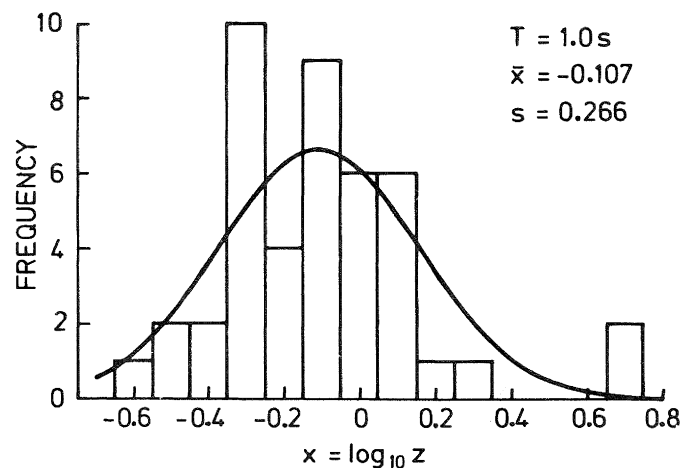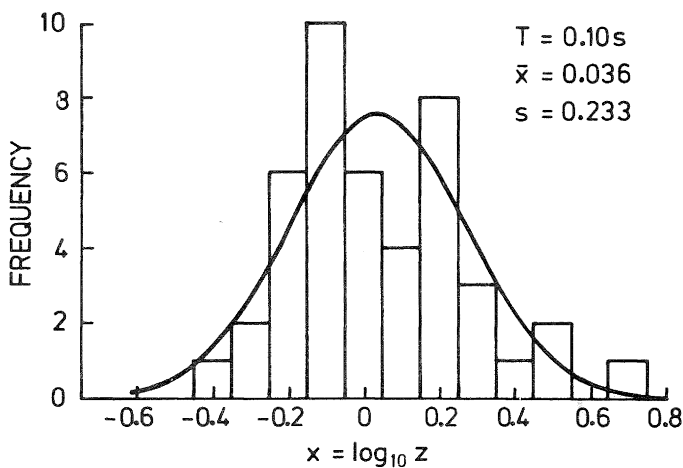
$T = 2.0$ s
$\bar{x} = -0.157$
$s = 0.239$
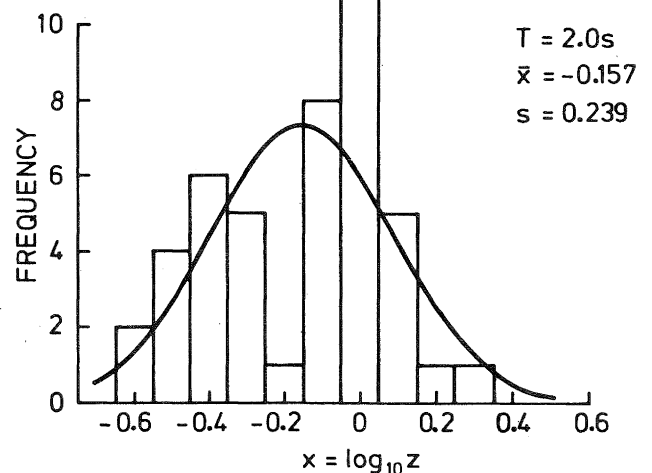
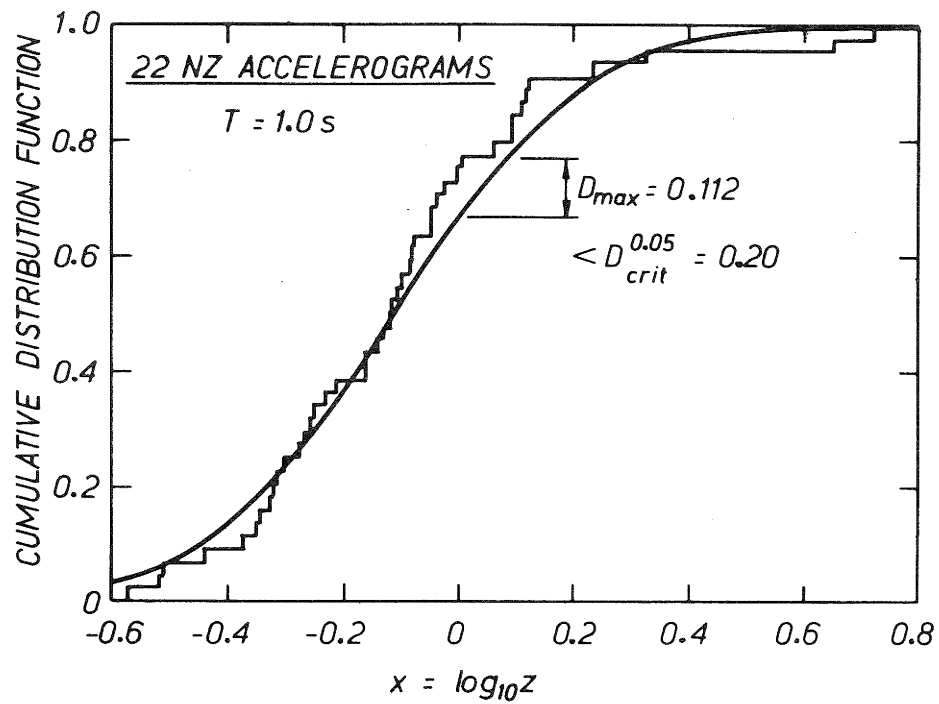Figure 3. Histograms of the log residuals at natural periods $T = 0.1$, 0.5, 1.0 and 2.0 seconds

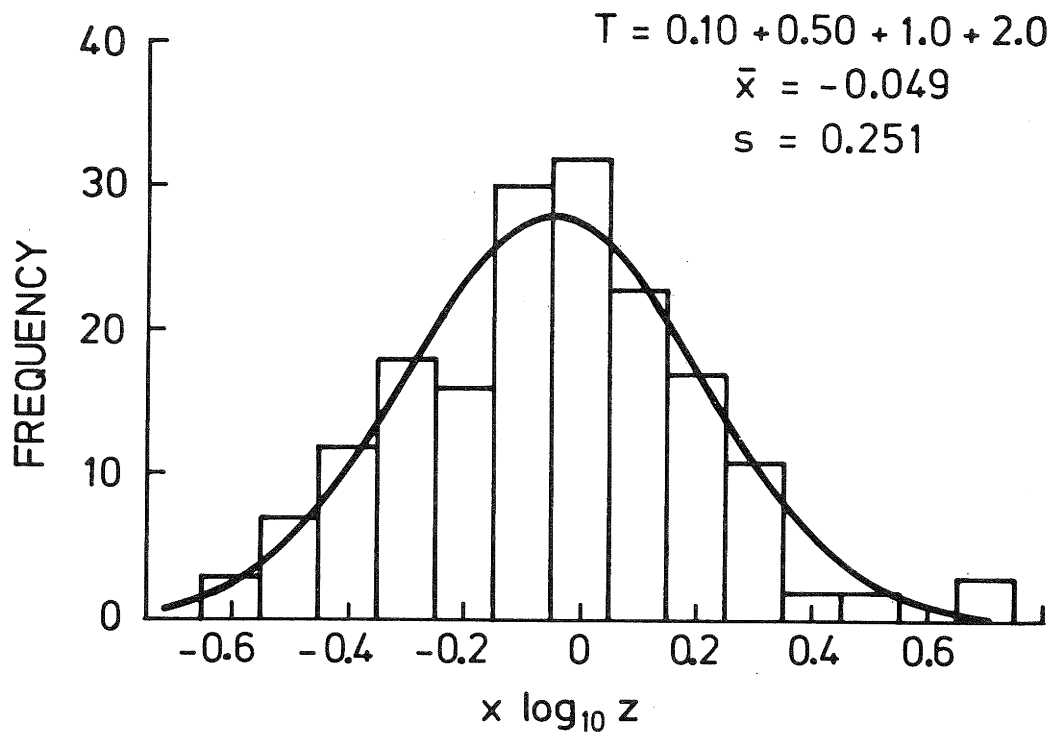Figure 4. Observed versus lognormal cumulative distributions for the case of worst fit, T = 1.0 s

Figure 5. Histogram of logarithmic residuals from samples at T = 0.1, 0.5, 1.5 and 2.0, lumped together

Accepting that Z is lognormally distributed, the problem becomes that of finding suitable values of the mean μ and standard deviation σ_{10} of x = $\log_{10}$ z to describe the distribution. In this article we shall focus principally on the determination of σ_{10}; the problem of appropriate values of the mean has been addressed by McVerry[19] in revising the Katayama law.

The principal question in determining an appropriate value of standard deviation σ_{10} to use in hazard analyses for New Zealand, is whether or not the sample of 22 accelerograms is representative of New Zealand ground motion. From Figure 1 it is seen that the recording sites are fairly well distributed throughout the main seismic region, if somewhat clustered locally. Given a larger set, it would perhaps be prudent to reduce the number of records from the Wellington region. On the other hand, since this is where the greatest risk lies, then perhaps the weighting towards Wellington is appropriate.

The other variables entering the hazard analysis are magnitude, epicentral distance and ground condition. These are plotted for our 22 accelerograms in Figure 6. Here it is evident that the set of accelerograms is far from complete. For example, except for the single Milford Sound record there is no earthquake with magnitude greater than six recorded at less than 60 km from its epicentre. It would be difficult to argue that these records represent damaging ground motions, and in fact damage at the recording sites was not great during any of the earthquakes. Nevertheless, we must make do with what we have, and it is certainly instructive to examine the New Zealand data for trends and for consistency, even if the study does not yield reliable working values of the scatter parameters.

Standard deviations of X period-by-period, taken from Table 3, are plotted in Figure 7. The individual values oscillate about the value of $\sigma_{10} = 0.254$ for the data as a whole. There is a slight trend of increasing σ_{10} with natural period, as observed by Trifunac et al.[16] and by McGuire[7] in US data, and Mitchell[17] in Japanese Japanese data. However, the trend is small compared with the variation between samples. The significance of the variations from period to period may be measured using the homogeneity of variance test[18]. Here

$$F_{max} = \frac{\text{largest variance}}{\text{smallest variance}} = \left(\frac{0.276}{0.202}\right)^2 = 1.87$$

This is less than the critical value of 2.65 at the five percent significance level. Hence the variations seen here are not necessarily significant, and the true value of standard deviation may well be invariant with respect to natural period.

A further test on the homogeneity of the data set may be made by dividing it randomly into two sets of 11 accelerograms. Standard deviations for these are given in Table 5. It can be seen the patterns of variation are not the same, suggesting further that the variations are due to the small size of the data set rather than true physical phenomena. This may be demonstrated more formally using the F-statistic. At three of the nine sampling periods a test that the two sets A and B are drawn from the same population fails, indicating that the samples are not representative. Note, however, that the estimates of 0.256 and 0.253 for the whole subsets, lumping the periods, are close to each other and to the value of 0.254 for the entire set (comprising 22 x 2 x 9 = 396, values of X). Again the F-statistic may be employed to support the assumption
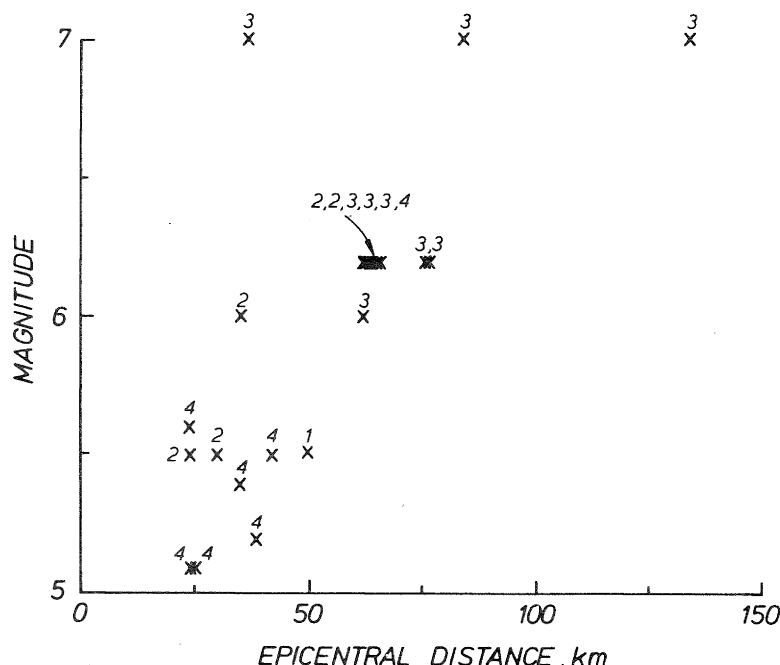

Figure 6. Magnitudes and distances of the 22 New Zealand accelerograms. Superscript numbers denote recording site ground conditions.
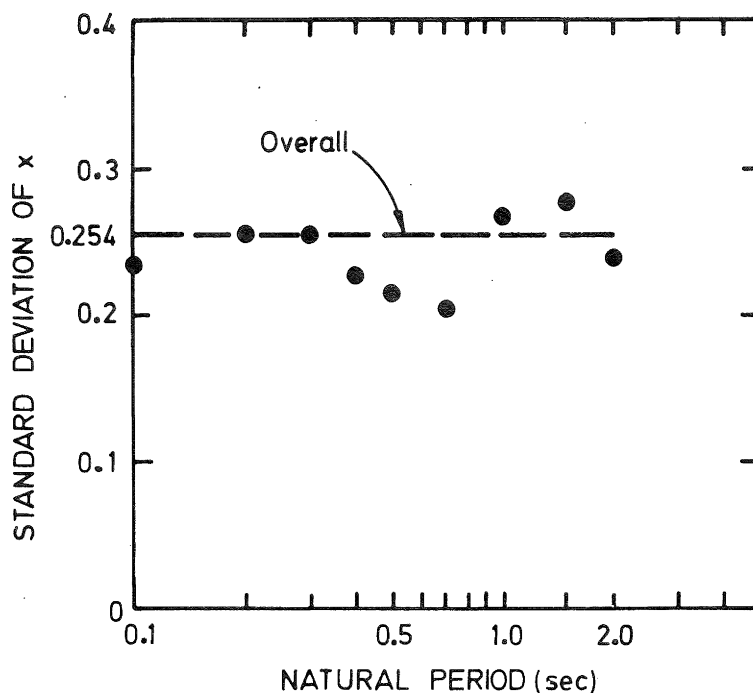
Figure 7.   Standard deviations of the logarithmic residuals

that sets A and B each taken as a whole
are apparently drawn from the same
population and that their sampling is
satisfactory.

Table 5.   Standard deviations of subsets of New Zealand data formed
by randomly selecting 11 accelerograms for Set A

Data Set	Natural Period, s									
	0.10	0.20	0.30	0.40	0.50	0.70	1.0	1.5	2.0	All
A (11 accelgms)	0.198	0.266	0.281	0.263	0.252	0.220	0.322	0.257	0.199	0.256
B (11 accelgms)	0.242	0.231	0.211	0.184	0.169	0.134	0.175	0.282	0.262	0.253
All 22 accelgms	0.233	0.255	0.255	0.227	0.213	0.202	0.266	0.276	0.239	0.254

Thus it appears that our data set is not adequate to resolve variations in standard deviation between natural periods should such variation actually exist. But it does provide an adequate sampling of small magnitude or distant New Zealand earthquakes to determine the overall value of σ_{10} = 0.254 for these sorts of events. However, it is not demonstrated that this subset of earthquakes is representative of New Zealand earthquakes as a whole.

Turning now to consideration of mean values of X, it is seen from the values near the bottom of Table 3 that at short periods the Katayama attenuation model has on the average underestimated the observed spectral amplitudes, most notably by 22 percent at T = 0.3 s. At long periods the model overestimates the data by up to 30 percent at T = 2.0 s, confirming the earlier impression given by Figure 2. While these results may justify strengthening the model at short periods, the average values at long periods may be less reliable because of the lack of large magnitude earthquakes in the data set.

CHOICE OF σ_{10} FOR HAZARD ANALYSIS

Since the present New Zealand data set is lacking in large earthquakes and close-in recordings, it is not clear that the value of $\sigma_{10} = 0.254$ is representative of all future New Zealand strong motion, especially for more damaging earthquakes. These misgivings are reinforced by comparing this value with those obtained elsewhere. Table 6 lists standard deviations estimated from other data sets. Only McGuire's values[7] are comparable to the New Zealand ones. However these were obtained from a small set of Western United States earthquakes that is probably more homogeneous than can be expected for New Zealand. On the other hand, one would expect Trifunac and Anderson's data[16], coming from a broader and therefore more varied selection of earthquakes, to be more scattered. Mitchell's values[17] shown in Table 6 were obtained from a study of the 277 accelerogram components of the Japanese data set of Katayama, Iwasaki and Seaki[11] from which the attenuation model was derived. Since the tectonic regime and site conditions of Japan are generally similar to those of New Zealand, it is probable that the distribution of scatter in the Japanese data roughly represents New Zealand conditions. The smaller values from the New Zealand data may be due to the small size of the data set, with the full range of possible conditions not covered.

As more records are obtained, more reliable estimates for New Zealand conditions will be possible. However, values of the scatter parameters are required now for hazard analyses. To overcome this difficulty, it is proposed that we lump the two sets of strong motion data, the New Zealand and Japanese sets, and take our working values from the combined set. In this way we are giving some weight to the New Zealand data, but at the same time recognising the greater coverage of the Japanese recordings and the general geologic similarities of the two countries. Combining the two data sets yields the values of σ_{10} shown in the bottom line of Table 6. These values are plotted in Figure 8, together with suggested values of σ_{10} for use in hazard analyses. They increase logarithmically with period from 0.1 to 1 sec, and are constant at $\sigma_{10} = 0.32$ for T > 1.0 s.

To assess the effect of the suggested values of σ_{10} on the results of a typical hazard analysis, uniform risk acceleration response spectra were computed for a Wellington site using first the value of $\sigma_{10} = 0.254$ indicated by the New Zealand data alone and second the recommended σ_{10} of 0.28 increasing to 0.32. The results are shown in normalized form in Figure 9. As expected, the difference is more marked at longer periods where the recommended values of σ_{10} are greater. The peak of the spectrum, which occurs at T = 0.2 s, is increased by just under 20 percent by the adoption of values recommended above.

Table 6. Comparison of σ estimates with those obtained elsewhere

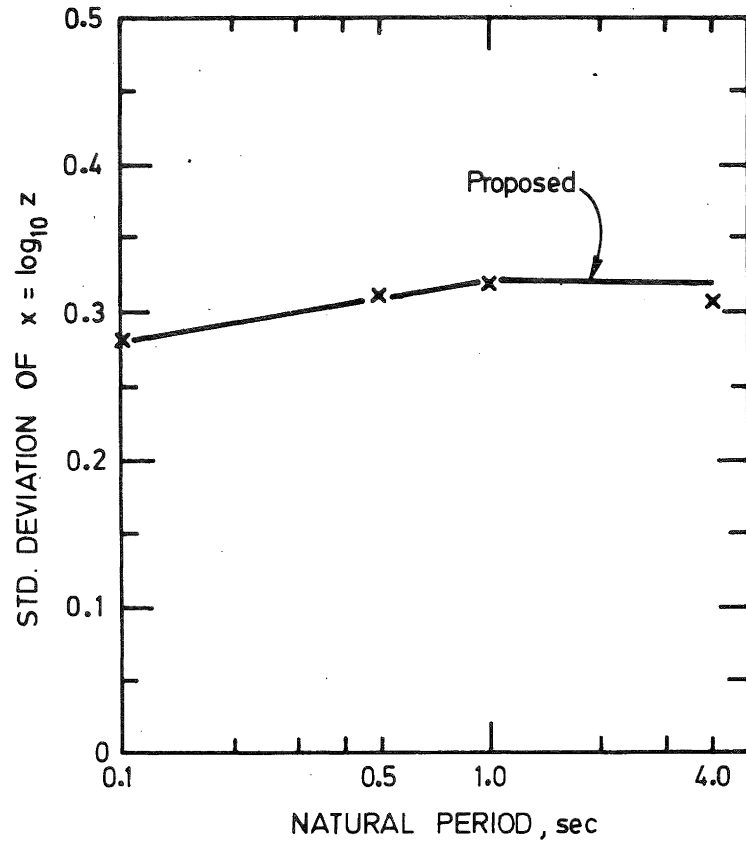| Period, sec	0.10	0.20	0.3	0.5	1.0	2.0	4.0
This study	0.233	0.255	0.253	0.213	0.266	0.239	–
McGuire[7] (Western US)	0.258	0.233	0.227	0.238	0.275	0.346	0.408
Trifunac and Anderson[16] (Western US)	0.36	–	0.37	0.38	0.41	0.45	0.50
Mitchell[17] (Japanese data)	0.288	–	–	0.320	0.325	–	0.303
New Zealand and Japanese data	0.281	–	–	0.310	0.319	–	0.303

Figure 8. Standard deviations from the combined Japanese-New Zealand data set. Solid line shows interim values of σ_{10} proposed for use in hazard analyses.
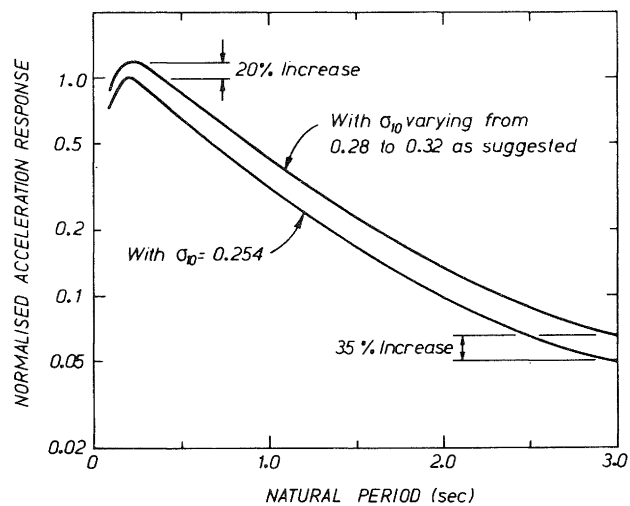

Figure 9. Comparison of uniform risk acceleration response spectra with $\sigma_{10} = 0.254$ (from New Zealand data alone) and σ_{10} as recommended in this article. The spectra are computed for five percent critical damping, a return period of 150 years, a minimum magnitude cutoff of M = 5.0 and ground condition 3 at Wellington.

SUMMARY AND CONCLUSIONS

Uncertainty in the attenuation law makes one of the main contributions to overall uncertainty in seismic hazard analyses, and it is important that it is allowed for in hazard computations.

The origins of attenuation uncertainty have been discussed in a companion paper[10]. In the present article, a set of 22 New Zealand strong motion accelerograms has been studied in an attempt to determine an appropriate distribution of scatter for use in correcting for attenuation uncertainty in hazard analyses for New Zealand. The following conclusions are drawn:

(1) It is found to a high level of confidence, that the residuals about the widely-used attenuation expression of Katayama, Iwasaki and Seaki are lognormally distributed. This conclusion should hold for New Zealand strong motion as a whole, despite the incompleteness of the New Zealand data set;

(2) The data set is not adequate to yield reliable estimates of the standard deviation of the logarithmic residuals at distinct natural periods. Lumping the data at the nine sampling periods in the band of 0.1 to 2.0 s yields the apparently reliable value of $\sigma_{10} = 0.254$.

However, it is noted that the data set comprises only two earthquakes larger than $M = 6$ ($M = 7$ and $M = 6.2$) and from these only one recording was obtained at an epicentral distance of less than 60 km. Thus the set is quite deficient in large earthquakes recorded at small distances. In fact, none of the recorded earthquakes caused much damage. Thus the value of $\sigma_{10} = 0.254$ is not necessarily representative of damaging New Zealand earthquakes. Comparison of the New Zealand results with those from more complete data sets recorded elsewhere confirms that the value of 0.254 should be used only with extreme caution.

(3) It is proposed, in the absence of a sufficiently complete set of New Zealand accelerograms, that the New Zealand data be combined with the Japanese data of Katayama et al. for estimating scatter or uncertainty parameters. The tectonic and geologic similarity of the two countries is advanced to justify this approach. The combined data set yields values of σ_{10} somewhat larger than 0.254 for the New Zealand data alone. It is suggested that the following values, taken from Figure 8, be employed until sufficient New Zealand data becomes available:

Period	0.10	0.20	0.30	0.5	0.7	≥1.0 s
σ_{10}	0.280	0.290	0.30	0.31	0.315	0.320

It is seen from Figure 9, that for typical conditions at a Wellington site, adopting these values increases the peak of the design spectrum by about 20 percent.

Finally, from the mean values of the New Zealand residuals it is seen that on the average, the Katayama, Iwasaki and Seaki attenuation expression moderately underestimates the short period spectral ordinates of the data set, by a maximum of 22 percent at $T = 0.3$ s, and overestimates the long period ordinates. In view of the uncertainty of the results at distinct natural periods and since the data set is lacking in long-period-rich large earthquakes, it would be imprudent to modify the attenuation model at long periods. As for the short period components, to be consistent with the proposal made above for estimating σ_{10}, any modification should be based on mean values calculated from the combined New Zealand-Japanese data set. Since the mean Japanese residuals are zero and the Japanese data comprises 277 components compared with 44 for the New Zealand set, the resulting mean residuals would be small (less than three percent under estimation). Thus for practical purposes, $\mu = 0$ may be employed.

REFERENCES

(1) Matuschka, T. (1980). "Assessment of Seismic Hazards in New Zealand." Dept. of Civ. Eng. Res. Report No. 222. Univ. of Auckland.

(2) Peek, R. (1980). "Estimation of Seismic Risk for New Zealand." Dept. of Civ. Eng. Res. Report 80-21. Univ. of Canterbury.

(3) Mulholland, W.M. (1982). "Estimation of Design Earthquake Motion for New Zealand." Dept. of Civ. Eng. Res. Report 82-9. Univ. of Canterbury.

(4) Mulholland, W.M. (1983). "Estimation of Design Earthquake Motions for New Zealand." Proc. 3rd South Pacific Conf. Earthq. Eng. Wellington, 20-35.

(5) Berrill, J.B., Priestley, M.J.N. and Chapman, H.E. (1980). "Design Earthquake Loading and Ductility Demand." Bull. N.Z. Nat. Soc. Earthq. Eng. 13: 232-241.

(6) Berrill, J.B., Priestley, M.J.N. and Peek, R. (1981). "Further Comments on Seismic Design Loads for Bridges." Bull. N.Z. Nat. Soc. Earthq. Eng. 14: 3-11.

(7) McGuire, R.K. (1974). "Seismic Structural Response Risk Analysis, Incorporating Peak Responses, Regressions on Earthquake Magnitude and Distance." Dept. of Civ. Eng. Res. Report R 74-51. MIT.

(8) Der Kiureghian, A. (1977). "Uncertainty Analysis in Seismic Rick Evaluation." Proc. 2nd ASCE Eng. Mech. Div. Specialty Conf. Raleigh N.C. 320-323.

(9) Bender, B. (1984). "Incorporating Acceleration Variability into Seismic Hazard Analysis." Bull. Seismol. Soc. Am 74: 1451-1462.

(10) Berrill, J.B. (1985). "Seismic Hazard and Design Loads." Bull. N.Z. Nat. Soc. Earthq. Eng. 18:139-150.

(11) Katayama, T., Iwasaki, T. and Seaki, M. (1978). "Statistical Analysis of Earthquake Acceleration Response Spectra." Trans. Japanese Soc. Civil Eng 10: 311-313.

(12) Ohashi, M., Kuribayashi, E., Iwasaki, T. and Kawashima, K. (1979). "An Overview of the State of Practice in Earthquake Resistant Design of Highway Bridges in Japan." Proc. Workshop on Research Needs of Seismic Problems Related to Bridges. San Diego, California.

(13) Specification for Earthquake Resistant Design of Highway Bridges. (1971) Japan Road Association.

(14) Hoel, P.G. (1971). Introduction to Mathematical Statistics. Wiley.

(15) Ang, A.H.S. and Tang, W.H. Probability concepts in Engineering Planning and Design. Wiley. New York.

(16) Trifinac, M.D. and Anderson, J.G. (1977). "Preliminary Empirical Models for Sealing Absolute Acceleration Spectra." Report CE 77-03. Univ. of Southern Calif.

(17) Mitchell, P.H. (1981). "The Distribution of Observed Earthquake Attenuation about the Model Proposed by Katayama et al. Unpublished Report. Univ. of Canterbury.

(18) Meddis, R. (1975). Statisitcal Handbook for Non-Statisticians. McGraw-Hill (U.K.).

(19) McVerry, G.H. (1985). "Uncertainties in Attenuation Relations for New Zealand Seismic Hazard Analyses." Paper presented at the annual conference of the Institute of Professional Engineers New Zealand. Wellington.