

SEISMIC HAZARD ANALYSIS AND DESIGN LOADS*

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SUMMARY

This article briefly reviews the seismic design load and zoning scheme proposed by the NZNSEE Bridge Study Group and discusses subsequent work in improving the underlying estimates of New Zealand seismic hazard. The loading scheme, published in 1980, was based on contemporary knowledge of seismic hazard in New Zealand and was innovative in its format which was chosen to give the designer flexibility in selecting the degree of ductility built into the structure, and the return period of the design motions.

Difficulty in estimating the design spectra for the NZNSEE study prompted a number of research projects at Canterbury University directed towards a thorough analysis of seismic hazard in New Zealand, expressed directly in terms of acceleration response spectra. These studies, together with complementary work by the SANZ Relative Earthquake Risk Subcommittee are described and discussed.

INTRODUCTION

In the six years since the 1978 NRB Bridge Design Seminar much effort has been expended in estimating appropriate levels of seismic design loads for structures in New Zealand. This paper is intended to summarise these studies and to examine some of the assumptions and uncertainties underlying the current estimations of seismic hazard in New Zealand.

The work with perhaps the greatest practical impact to appear during this period is that of the New Zealand National Society for Earthquake Engineering's (NZNSEE) Bridge Study Group, which published a draft code for the earthquake-resistant design¹ of bridges. While the loadings section of the proposed code was novel in both its format and its technical details, the principal innovations are found in its format, which allows the designer freedom to choose the degree of ductility given to the structure and the level of seismic hazard to which it is exposed, through choice of return period. On the technical side, the elastic acceleration response spectra underlying the seismic coefficients were estimated from contemporary studies of New Zealand's seismic hazard by Matuschka² and Smith³, and a period-dependent force

reduction factor was used to obtain inelastic response coefficients from the elastic spectra. Also, although three seismic zones were used as in the pre-existing scheme, jumps in seismic load between zones were avoided by introducing a smooth transition from zone A to zone C within an intermediate zone.

The form of the base shear expression is as follows:

$$H = C_{H\mu}(T, \mu) Z_H(\tau) Mg \quad (1)$$

where Mg is the participating seismic weight, Z_H is a coefficient depending on return period τ of the design motion, and $C_{H\mu}$ is a horizontal force coefficient derived from the relation

$$C_{H\mu} = \frac{S_a(T)}{R(\mu, T)} \quad (2)$$

In (2), $S_a(T)$ [or C_{HE} in the original work] is the corresponding elastic absolute acceleration response spectrum, a function of natural period T and an assumed 5 percent equivalent viscous damping. $R(\mu, T)$ is a force-reduction factor allowing for inelastic response, and depends on both the ductility capacity of the structure and period. The return period coefficient Z_H is normalised to a value of unity at $\tau = 150$ years. Thus S_a represents the response spectrum of ground motion with a return period of 150 years.

This loading scheme has already been discussed at length in the original commentary⁴, a subsequent extended commentary⁵, and in the paper of Priestley and Park⁵. In the latter, the inelastic

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spectra and the zoning map contours have been redrawn following the work of Peek^{4,6}. These figures will not be reproduced here. Instead, we shall focus on the problem of estimating likely ground motion in New Zealand, expressed in the form of elastic acceleration response spectra. This step was the weakest part of the proposed bridge loading scheme, and has been the object of subsequent research.

Our knowledge of the mechanics of earthquakes and of values of the material properties involved is far from complete. Therefore, to estimate likely ground shaking, we must resort to empirical models and probability theory. Furthermore, since there are no New Zealand recordings of significantly strong ground shaking and few of moderate motions, we must rely very heavily on overseas data and models, introducing further uncertainty.

The probabilistic estimation of earthquake motions was formerly known as seismic risk analysis; now, by UNESCO decree, as seismic hazard analysis in order to distinguish between the overall risk of damage (a function also of vulnerability of the structure) and the natural hazard itself. Before discussing the hazard analyses prompted by the Bridge Group's work, we will briefly examine the general analysis procedure.

REVIEW OF SEISMIC HAZARD ANALYSIS

Seismic hazard analysis was formulated on a probabilistic basis by C A Cornell⁸ in the late 1960s. It relies upon two separate models: a seismicity model describing the geographical distribution of earthquakes, and the distribution of earthquake magnitude; and an attenuation model describing the effect produced at a site away from the source of the earthquake, as a function of magnitude and source-to-site distance. These two basic elements, together with some results from the theory of probability, yield estimates of the probability that a given strength of shaking will be exceeded at the site during a one-year interval. It is common to express this annual probability of exceedence by its reciprocal, return period.

A seismicity model comprises a number of source regions, together with appropriate values of the parameters a and b in the Gutenberg and Richter recurrence relation,

$$\log n = a - b m \quad (3)$$

where n is the number of earthquakes with magnitude exceeding m per year. The source regions may be lines, representing faults, or areas of uniform seismicity representing domains of diffuse seismicity. Some models also attach a magnitude bound, m_{\max} , to each source region. The quantity 10^a gives the total number of earthquakes per year, per unit length in the case of a line source and per unit area in the other case.

The most recent seismicity model for New Zealand, that of Smith, Lensen and Berryman⁷, is shown in Figure 1. Two other recent seismicity models are due to Matuschka² and Peek⁹. Peek's model is shown in Figure 2. These models are derived chiefly from geological data in determining boundaries of the source region and from seismological records in determining values of the seismicity parameters. They have some input from post-glacial fault offset observations, but for the most part the models are based on the seismic record of the past 140 years.

Attenuation models relate the effect i at a site to magnitude and distance. In general we have

$$i = i(m, r) \quad (4)$$

which may be inverted to give the magnitude necessary to just produce effect i at a distance of r . That is

$$m = m(i, r) \quad (5)$$

A common form of attenuation relation, which we shall call McGuire's form, is as follows:

$$\log i = b_1 + b_2 m - b_3 \log (r + 25) \quad (6)$$

where b_1 , b_2 and b_3 are empirically determined coefficients. The "25" is intended to prevent unbounded effects at sites close to the source. In the form of (5), (6) becomes

$$m = \frac{1}{b_2} \left\{ \log [i(r + 25)^{b_3}] - b_1 \right\} \quad (7)$$

Combining the two models leads to the following expression for the probability p_i that any earthquake occurring at random in the source region will produce motion with strength exceeding i at the site:

$$p_i = P[I > i] = \int_{\text{source}} 10^{-bm(i, r)} f_R(r) dr \quad (8)$$

where $f_R(r)$ = the probability density function of distance r .

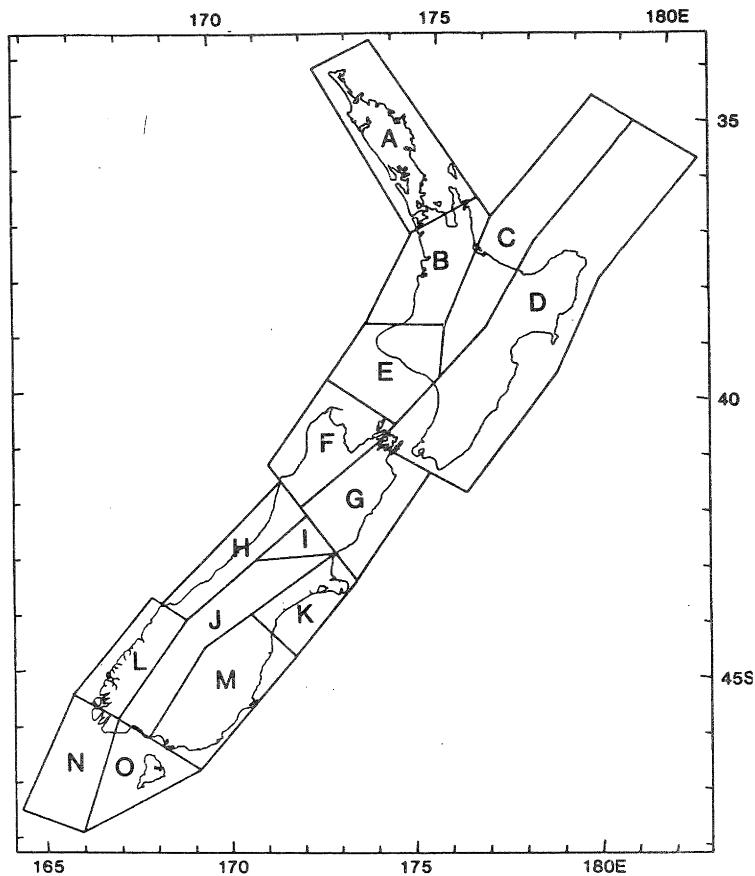
Usually (8) must be evaluated numerically.

The probability p_i applies to any earthquake occurring with random position (and magnitude) in the source region. Therefore, if there are on the average N earthquakes per year in the source region, then the average annual probability of i being exceeded at the site is

$$p_D = p_i N \quad (9)$$

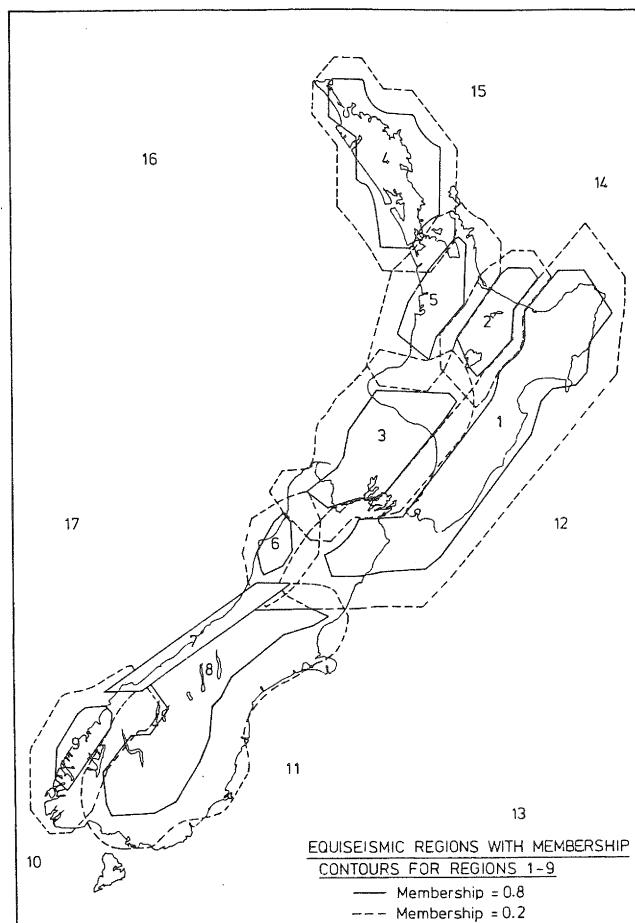
and the return period of motion exceeding i is

$$\tau_i = 1/p_D = 1/p_i N \quad (10)$$



Region	Area sq km	b	M_{max}	1965-82 N_4 a_4	1942-82 N_5 a_4	1840-1982 $N_{6.5}$ a_4	a_4 chosen
A	54,028	1.2	7.5	3 0.003	4 0.029	0	0.03
B	34,288	1.2	8.0	36 0.058	5 0.056	0	0.10
C	23,224	1.2	7.5	185 0.443	21 0.350	1 0.321	0.45
D	89,867	1.13	8.5	687 0.125	159 0.582	16 0.837	0.85
E	31,428	1.15	8.5	148 0.262	22 0.241	5 0.838	0.80
F	31,460	1.13	8.5	280 0.495	29 0.304	5 0.746	0.70
G	35,434	1.1	8.5	154 0.242	43 0.373	4 0.447	0.60
H	24,366	1.05	8.5	45 0.102	12 0.135	0	0.20
I	6,793	1.1	8.5	19 0.156	7 0.317	1 0.583	0.40
J	30,824	1.1	8.0	41 0.074	11 0.110	0	0.11
K	19,368	1.1	8.0	10 0.029	2 0.032	0	0.03
L	26,500	0.95	8.5	316 0.662	78 0.640	4 0.253	0.70
M	43,971	1.1	8.0	16 0.020	6 0.042	0	0.08
N	31,931	1.0	8.5	296 0.515	40 0.306	5 0.350	0.60
O	19,304	1.1	8.0	8 0.023	5 0.080	0	0.08

Figure 1 The Smith, Lensen, Berryman Seismicity Model



Region Number	Area (1000 km ²)	a_4	b
1	110.85	0.58	1.10
2	20.77	0.20	1.25
3	50.88	0.25	1.10
4	56.24	0.005	1.00
5	32.11	0.11	1.16
6	12.11	0.67	1.10
7	10.69	0.24	0.90
8	79.80	0.09	1.10
9	23.66	0.50	0.98
10	28.75	0.20	0.87
11	209.72	0.003	0.81
12	160.80	0.14	1.28
13	218.27	0.00	1.00
14	104.98	0.31	1.00
15	101.95	0.005	1.00
16	613.25	0.005	1.00
17	197.46	0.02	0.95

Figure 2 Peek's Seismicity Model⁹

SEISMICITY MODELS FOR NEW ZEALAND

The two most recent seismicity models are due to Smith, Lensen and Berryman (the SLB model) published in 1983, and Peek et al which appeared three years earlier. In general concept and in most details the two models are quite similar.

Parameter values of the models are compared in Table 1, with reference to the SLB regionalisation. The parameter a_4 used to measure activity rate gives the annual number of earthquakes with $M \geq 4$ per 1000 km². Therefore, in terms of the Gutenberg and Richter parameters a and b , $a_4 = 10^{(a-4b)}$. The other parameter shown, $N_{6.5}$, denotes the number of earthquakes with $M \geq 6.5$ observed or predicted by the models for the region as a whole during the period 1840 to 1982. Since these earthquakes contribute the greatest hazard, the $N_{6.5}$ values provide a very useful check.

We see that in general the activity rate of the SLB model is greater than that of the Peek model, predicting 58 earthquakes with $M \geq 6.5$ since 1840 compared with the 43 observed. At first sight, it seems that the SLB model is excessively conservative. However, if we remove eleven of the 20 earthquakes predicted for the Fiordland region (regions L and N) so that the number predicted agrees with the nine observed earthquakes, the overall total comes to 47, identical to that of the Peek model, and not far from the observed number of 43.

Other significant differences in detail between the models occur in the Otago, Taranaki and Alpine Fault areas. On the east coast of the South Island, the SLB model has separate zones for eastern Otago (M) and Canterbury on the grounds of geologic differences, whereas Peek has a single zone here. Clearly, the geologic character of the two regions is different and the adoption of distinct zones is reasonable.

As for the Taranaki area, it is difficult to believe that the long-term seismicity of this region (with $a_4 = 0.80$) is almost as high as that of the main seismic region (zone D with $a_4 = 0.85$) along the east coast of the North Island. Certainly there have been large historic earthquakes in the Taranaki region, but the author considers that the present value of a_4 in zone E requires strong justification.

In the Alpine Fault region, zone H, historical seismicity is very low but there is geological evidence (Adams¹⁰) of $M \geq 8$ earthquakes about once every 500 years. The SLB model gives a return period for $M \geq 8$ of 4600 years and the Peek model, 1500 years. Since the last such earthquake occurred about 500 years ago, a higher activity rate than either model provides would seem prudent. Values of $a_4 = 0.50$ and $b = 0.90$ together with the present $M_{\text{max}} = 8.5$ in the SLB zone H would give a return period of 500 years

for $M \geq 8$ events.

We may conclude that the SLB model is currently the best available, but the reasons for adopting such a high value of a_4 in the Taranaki region should be examined carefully. Also, the overall activity rate might be reduced by 10 percent, to bring the predicted and observed numbers of $M \geq 6.5$ earthquakes into agreement, and the Alpine Fault region parameters might be revised to increase the predicted likelihood of great earthquakes on the fault.

ATTENUATION MODELS

For the majority of uses, the most suitable description of design ground motion is in the form of a response spectrum. It can be used directly to estimate structural response, and can form the basis for the generation of artificial accelerograms as described by Sharpe in this seminar.

Formerly, the chief method of determining design spectra comprised two steps: first peak ground acceleration, velocity and displacement were estimated for the site; then the design spectrum was constructed from them. However, it seems intuitively clear, and has been confirmed by Cornell, Banon and Shakes¹¹, that fewer errors would be introduced by estimating response spectra directly. Hence this approach was adopted in the hazard analyses of Peek⁴ and Mulholland¹².

Since there were not enough New Zealand strong motion data from which to derive an attenuation relation, three models based on foreign data were examined. These were the models of Bentley¹³, McGuire¹⁴ and Katayama et al¹⁵. The models have been discussed in detail by Peek⁴ and Mulholland¹². The Katayama model was chosen for the hazard analyses for the following reasons:

1. It is based on data from Japan, whose tectonics and geology are generally similar to those of New Zealand.
2. Statistics are given describing the scatter of data about the mean.
3. Allowance is made for local ground conditions.
4. It fits the limited New Zealand data fairly well.

The latter point is illustrated by Figure 3, from one of the strongest New Zealand accelerograms. However, scatter about the model predictions is large, as seen from Figures 4 and 5. This points up the necessity of allowing for uncertainty in the attenuation model, as discussed in the following section. Figures 3, 4 and 5 were taken from Mulholland's 1981 study¹². Since then, several further accelerograms have been processed by the Engineering Seismology section of the DSIR, which in connection with NZS 4203 revisions is at present undertaking a further assessment of

Region (SLB)	Area (1000 km ²)	N _{6.5} historical	Smith and Berryman			Peek et al		
			a ₄	b	N _{6.5} implied	a ₄	b	N _{6.5} implied
A	54.0	0	0.03	1.2	0.23	0.005	1.0	0.12
B	34.3	0	0.10	1.2	0.49	0.11	1.16	0.67
C	23.2	1	0.45	1.2	1.5	0.20	1.25	0.49
D	89.9	16	0.85	1.13	16	0.575	1.10	13.2
E	31.4	5	0.80	1.15	4.8	0.253	1.10	2.2
F	31.5	5	0.70	1.13	4.7	(0.67)*	(1.10)	(5.3)
G	35.4	4	0.60	1.1	5.4	0.575	1.10	5.1
H	24.4	0	0.20	1.05	1.6	0.24	0.90	4.7
I	6.8	1	0.40	1.1	0.7	(0.33)*	(1.10)	(0.57)
J	30.8	0	0.11	1.1	0.9	0.09	1.10	0.70
K	19.4	0	0.03	1.1	0.15	(0.02)*	(1.10)	(0.10)
L	26.5	4	0.70	0.95	11.1	0.50	0.98	6.7
M	44.0	0	0.08	1.1	0.9	(0.072)*	(1.10)	0.80
N	31.9	5	0.60	1.0	8.6	0.20	0.87	6.1
O	19.3	0	0.08	1.1	0.39	(0.08)*	(1.1)	(0.4)
Total =	502.8	41**	a ₄ = 0.43	58		a ₄ = 0.29	47	

* Regions not directly comparable

** Table 2, reference 7 gives a total of 43 historical earthquakes.

Table 1 Comparison of Seismicity Models

attenuation models.

$$p_i^* = P[I > i^*]$$

ALLOWANCE FOR UNCERTAINTY IN ATTENUATION

Attenuation models such as Katayama's are determined by fitting curves to scattered data such as that shown, for example, in Figure 6.

The model, therefore, represents mean behaviour, with the pattern of scatter in the observed data suggesting the likely distribution of future events. In our analysis, we may allow for scatter by introducing a random variable z into the attenuation model as follows:

$$i^* = z i(m, r) \quad (11)$$

In (11), $i(m, r)$ is the mean attenuation function as before [equation (4)]; the random variable z measures the factor by which intensities of motion at individual sites differ from the mean behaviour.

The inverse relation then becomes

$$m = m \left[\frac{i^*}{z}, r \right] \quad (12)$$

and equation (8) may be rewritten as

$$= \int \int 10^{-bm} \left[\frac{i^*}{z}, r \right] f_R(r) f_Z(z) dr dz \quad (13)$$

To find the effect of uncertainty, we must first know the probability distribution of z . Theoretical considerations, together with observations, suggest that z is lognormally distributed. Let μ and σ equal the mean and standard deviation of $\ln z$. By substituting the lognormal distribution for $f_Z(z)$ and integrating (13) using McGuire's expression (7) for $m(i^*/z, r)$, we can show that the corrected probability

$$p_i^* = A_z p_i \quad (14)$$

where

$$A_z = \exp \left[\frac{\mu}{\sigma} \frac{b}{b_2} + \frac{1}{2} \left(\frac{\sigma}{b_2} \right)^2 \right]$$

If the model correctly predicts the mean of our data, then the mean value of z equals unity, so that $\mu = 0$ and

$$A_z = \exp \left[\frac{1}{2} \left(\frac{\sigma}{b_2} \right)^2 \right] \quad (15)$$

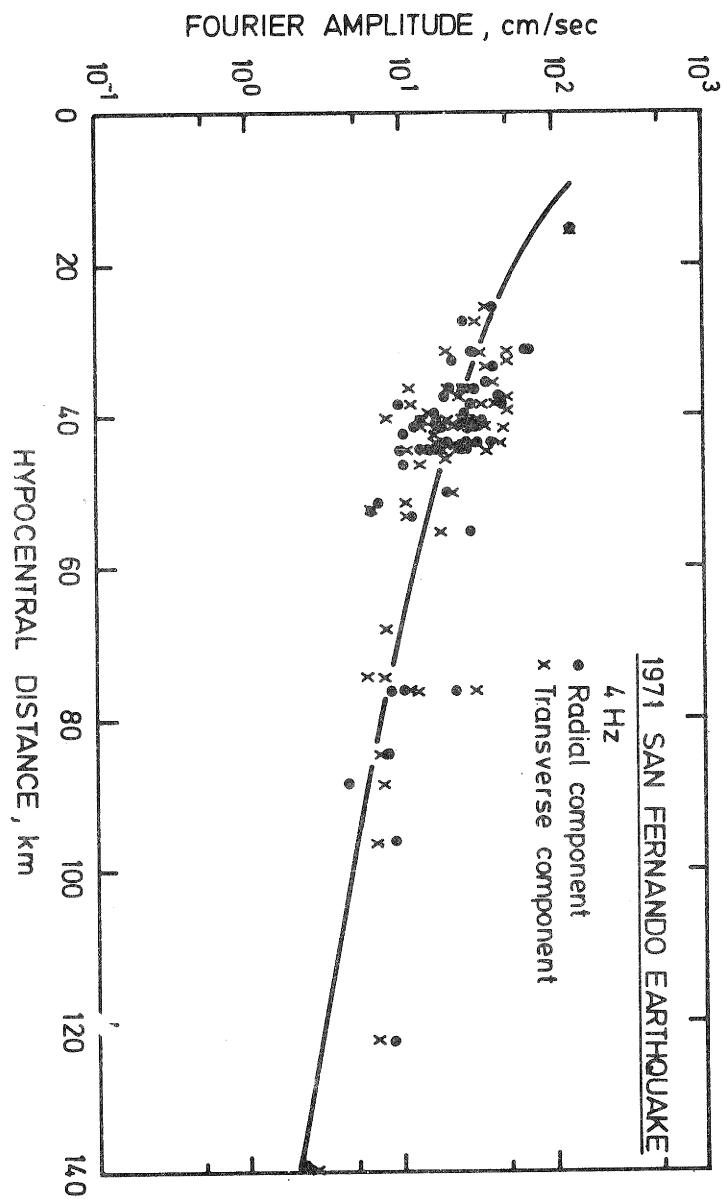


Figure 6. Typical attenuation data.

Figure 5.

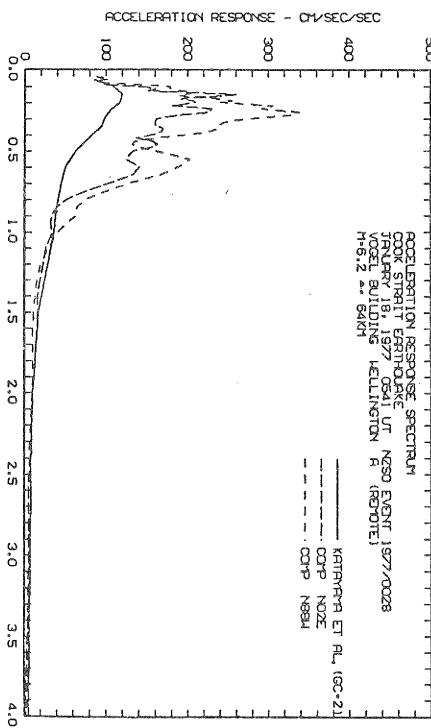


Figure 4.

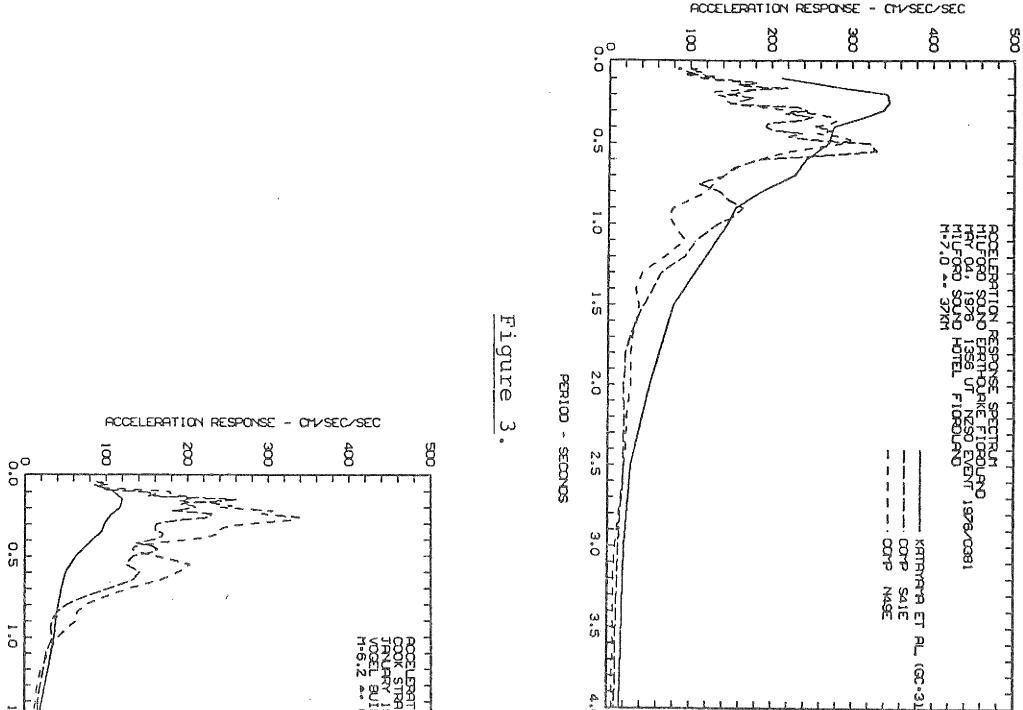


Figure 3.

Similarly, annual probabilities of damage P_D and return periods are corrected for uncertainty by multiplying or dividing by A_z respectively.

When we wish to find the effect of uncertainty on spectral amplitudes predicted for a given return period, the problem is a little different. In this case, the corrected amplitude i^* is given by

$$i^* = B_z i \quad (16)$$

where B_z is an enhancement factor given by the expression

$$B_z = \exp\left(\frac{1}{2} \frac{\sigma^2 b}{b^2}\right), \quad (17)$$

The effect of uncertainty is large, as the values of B_z in Table 2 for McGuire's model for 5 percent-damped spectral accelerations show. B_z for this model ranges from 1.6 to 2.5.

The term "uncertainty" is unfortunate since it implies that the effect is an artificial one, and that a better understanding of attenuation would lead to lower enhancement factors. This is not strictly correct. The scatter of observed data about the attenuation model has two causes; one in the natural variation in shaking from site to site, the other in the inability of the model to match the real mean behaviour. Provided the model is sufficiently flexible in form to follow the mean trend in the data reasonably well, the major cause of scatter is the natural (and very real) variation between apparently similar sites. These variations are caused by some sites lying along paths that are more efficient transmitters of seismic waves than others, by local "site effects" and by details of the source radiation pattern; all real phenomena. The enhancement effect arises from the way in which "low attenuation" sites ($z > 1$) interact with the distribution of magnitudes. Because of the exponential distribution of magnitudes, low attenuation sites are shaken at a given intensity by many more earthquakes than are "high attenuation" ($z < 1$) sites. This can be seen from (13), where an increase in z clearly increases the 10^z term. The added contribution to the hazard due to low attenuation sites is not compensated for by corresponding high attenuation sites since the number of earthquakes that will produce the given intensity at these sites is very much smaller. These effects are illustrated by the example given in the appendix.

Because of the large magnitude of the enhancement factor, it is important that it be estimated as accurately as possible. Since McGuire's model was determined from a fairly small set of western United States earthquakes it

is likely that appropriate values of B_z for New Zealand will be as large as those in Table 2. On the one hand, the greater tectonic variety of Japan and New Zealand should lead to greater scatter than found in the more geologically homogeneous western United States region. On the other, the greater flexibility of the Katayama model, especially with the inclusion of a variable for site conditions, should reduce the scatter due to model rigidity.

Table 2 McGuire's Attenuation Model for 5% Damped Acceleration Response

$$\log S_a = b_1 + b_2 m - b_3 \log(r + 25)^*$$

Period (sec)	b_1	b_2	b_3	σ_{10}^{**}	B_z
0.10	3.173	0.233	1.341	0.258	2.30
0.20	3.373	0.226	1.323	0.233	2.01
0.30	3.144	0.290	1.416	0.227	1.68
0.50	2.234	0.356	1.197	0.238	1.59
1.00	0.801	0.399	0.704	0.275	1.74
2.00	-0.071	0.466	0.675	0.346	2.11
4.00	-0.620	0.520	0.788	0.408	2.54

* S_a in cm/s^2 ; r = hypocentral distance in km

** σ_{10} is the standard deviation of $\log_{10} z$.
 $\sigma = 2.3 \sigma_{10}$

Preliminary estimates of B_z based partly on Mulholland's comparison of New Zealand accelerograms with the corrected Katayama model are presented in Table 3. This study is continuing, using the larger set of accelerograms now available. In the meantime, it would be prudent to use the larger of the two values from Tables 2 and 3 at the period of interest.

Table 3 Preliminary Estimates of the Enhancement Factor B_z for the Katayama Model as Modified by Mulholland¹².

Period (sec)	Equivalent b_2	σ_{10}^*	B_z
0.1	0.13	0.22	3.1
0.2	0.20	0.254	2.6
0.3	0.24	0.249	2.1
0.5	0.35	0.246	1.7
1.0	0.43	0.186	1.3
1.5	0.47	0.238	1.4
2.0	0.39	0.258	1.6
4.0	0.35	0.138	1.2

* The quotes are employed since a site that lies on a "low" attenuation path for one earthquake will not necessarily do so for others.

* From Table 2.7 of Mulholland¹².

RESULTS

Peek⁶ and Mulholland^{12,16} have developed computer programmes to evaluate expressions (8) and (10) using Katayama's attenuation expression and a selection of seismicity models. Their results are presented in the form of uniform risk acceleration response spectra (with 5 percent damping) in which spectral ordinates are computed corresponding to a specified return period for a given site.

They have computed risk spectra for a grid of sites covering the country and found that spectral shape does not vary greatly with geographical position. Hence, an average spectrum can be computed together with a contour map of scaling factors as shown in Figures 7, 8 and 9. These spectra are drawn for Katayama's ground condition type I, tertiary or older rock, the stiffest of his four categories. (Types III and IV, alluvium of less than or greater than 25 metres in depth respectively, would be more typical of New Zealand sites.) The spectra have been corrected for attenuation uncertainty using a constant value of $\sigma_{10} = 0.23$. By comparison with the values in Table 2, this correction is probably too small. We should note also that the "Smith and Berryman" seismicity model is a preliminary version of the SLB model discussed earlier and should give slightly larger spectral ordinates than the final model.

CONCLUSIONS

Since the 1978 NRB Bridge Seminar we have seen considerable effort and hopefully some progress towards more rational seismic design loads for bridges, and indeed, all structures. The seminal event was the formation of the NZNSEE Bridge Study Group, and the decision of its chairman to insist on the group writing its findings in the form of code and commentary.

This resulted in a loading specification that contained innovations in format, allowing much flexibility in design strategy. It also pointed up a weakness in our knowledge of seismic hazard in New Zealand, prompting the studies of Peek and Mulholland, the latter drawing on the concurrent work within the DSIR of Smith, Lensen and Berryman.

At present we are close to seeing the fruition of these studies in the form of a thorough seismic hazard analysis for the country, nearing completion in the hands of the Seismic Risk Subcommittee of the Standards Association.

We have the carefully conceived SLB seismicity model, agreeing in most respects with the independent study of Peek. However, we noted that the activity rate given by the SLB model seemed high in the Taranaki region and perhaps low in the Alpine Fault region.

The other component of a hazard

analysis, the attenuation model, is not as well developed. Nevertheless, it is expected that current work in verifying the Katayama model against the now extended New Zealand strong motion data set will yield a model which should perform adequately. Special mention should be made of the importance of allowing for uncertainty in the attenuation model. Having a greater number of New Zealand data available should lead to large improvements.

It would be premature to speculate too much on the likely final results of the study being made for the Loadings Code revisions, beyond pointing to the interim work of Mulholland, shown in Figures 7, 8 and 9. Figures 8 and 9 indicate the variation in hazard about the country. The shape of the final design spectrum is likely to vary substantially from that of Figure 7 due to modifications to the attenuation model itself, improved estimates of $B_z(T)$ allowing for uncertainty, and from the choice of more typical ground conditions for the basic spectrum. In this regard, we note that the majority (62 percent) of Katayama's data came from Type III sites (alluvium less than 25 metres deep). This is likely, also, to be the most common site condition in New Zealand, and in the author's opinion would be the appropriate choice for the basic design spectrum. This could be modified in a simple fashion for exceptionally soft or exceptionally hard sites.

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APPENDIX

ILLUSTRATION OF MODEL UNCERTAINTY

The following example, using a single point source region, illustrates the effect of scatter about the mean attenuation curve. A point source is chosen to simplify the arithmetic; the effect of uncertainty is similar for line and area sources.

Consider a site 50 km from the point source which has the seismicity parameters $a = 3.33$ and $b = 1$. Suppose

we seek the annual probability that acceleration response at a natural period of $T = 0.3$ s and with 5 percent damping, will exceed the value of 100 cm/s^2 at the site. We assume that the attenuation relation

$$\log S_a = 3.0 + 0.33 m - 1.5 \log (r + 25) \quad (A1)$$

is appropriate, where S_a is in cm/s^2 and r in km.

To find the annual probability of S_a exceeding $s = 100 \text{ cm/s}^2$ we must first evaluate equation

$$P_s = P[S_a > s = 100]$$

$$= \int_{z=0}^{\infty} \int 10^{-bm} \left(\frac{s}{z}, r \right) f_R(r) f_Z(z) dr dz \quad (A2)$$

to find the probability of exceedence in any single earthquake. Since $R = 50 \text{ km}$, a constant, (A2) reduces to

$$p_s = \int_{z=0}^{\infty} 10^{-bm} \left(\frac{s}{z}, r \right) f_Z(z) dz \quad (A3)$$

The annual probability is then found by multiplying by the total annual number of earthquakes.

Case 1 No Scatter About Attenuation Model

Rearranging (A1) to give $m(s/z, r)$ and substituting $s = 100 \text{ cm/s}^2$ and $r = 50 \text{ km}$, we have in general,

$$m = 5.44 - 3 \log z \quad (A4)$$

With no scatter, $z = 1$ and $m = 5.44$. Also, in this case,

$$f_Z(z) = 1 \text{ for } z = 1 \\ 0 \text{ for } z \neq 1 \quad (A5)$$

Substituting into (A3), therefore, gives

$$p_s = 10^{-5.44} = 3.63 \times 10^{-6}$$

But for $z = 3.3$ we have a total of $N = 10^{3.3}$ earthquakes with $M \geq 0$ per year. Hence the annual probability of damages is

$$p_D = N p_s = 10^{3.3} \cdot 10^{-5.44} = 7.24 \times 10^{-3}$$

$$\text{or } \tau_s = 1/p_D = 138 \text{ years.}$$

Case 2 With Scatter

Suppose now that there is scatter about the mean attenuation curve. Again for illustration, we adopt a simple, discrete distribution of z as follows:

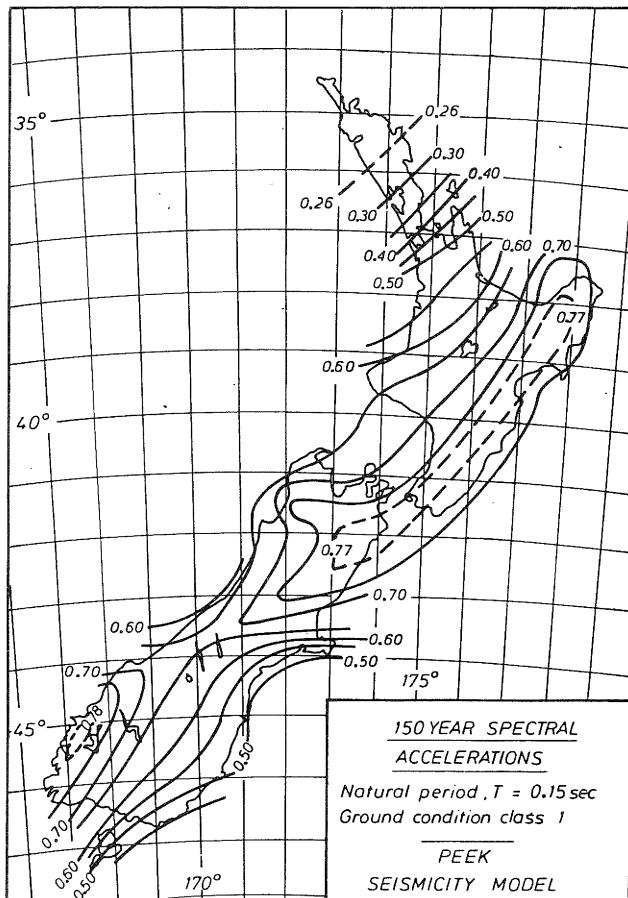


Figure 8

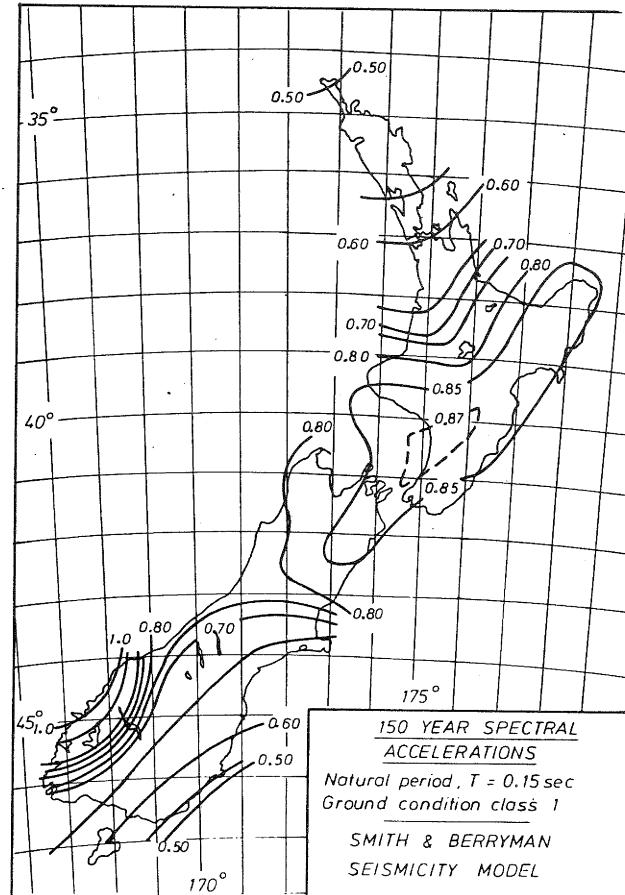


Figure 9

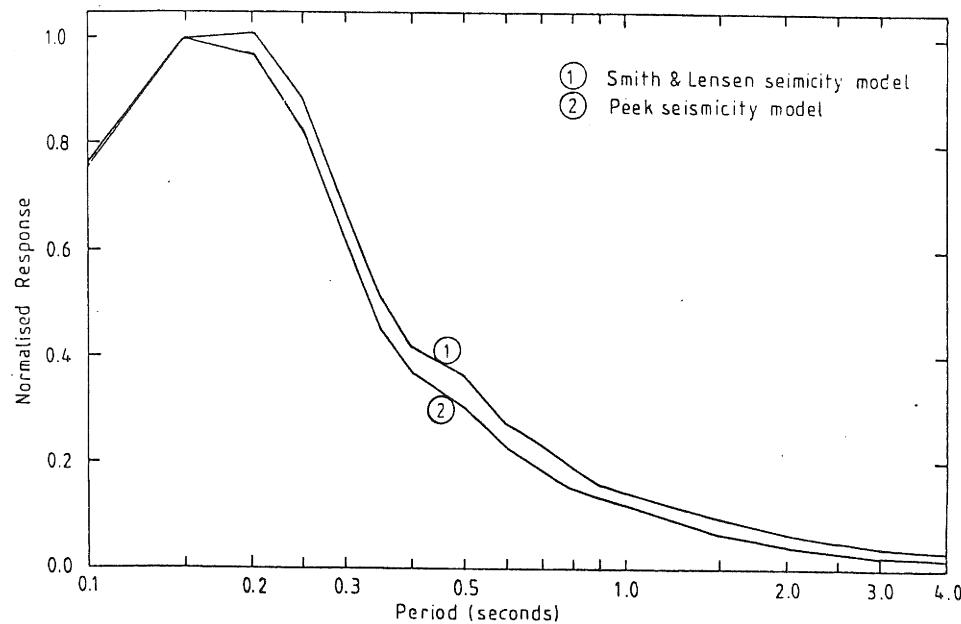


Figure 7. Comparison of Normalised Risk Spectra from both Seismicity Models for Haywards (Ground Class 1, 150 year Return Period).

$$\begin{aligned}
 f_Z(z) &= 0.2 \text{ when } z = 2 \\
 &= 0.6 \text{ when } z = 1 \\
 &= 0.2 \text{ when } z = 0.5 \\
 &= 0 \text{ elsewhere}
 \end{aligned}$$

For $z = 0.5, 1$ and 2 , we have from (A4) that $m(100/z, r)$ equals $6.33, 5.44$ and 4.53 respectively. Now equation (A3) becomes

$$\begin{aligned}
 p_s &= 0.2 \times 10^{-6.33} + 0.6 \times 10^{-5.44} + 0.2 \times 10^{-4.53} \\
 &= 9.35 \times 10^{-8} + 2.18 \times 10^{-6} + \underline{5.90 \times 10^{-6}} \\
 &= 8.17 \times 10^{-6}
 \end{aligned}$$

Notice that it is the third term that dominates in this case, and that it is associated with earthquakes with $M \geq 4.53$. Since there are nearly ten times as many of these earthquakes as there are earthquakes with $M \geq 5.44$, the sole contributor in Case 1, this term is larger overall. The final value of p_s with scatter considered is $8.17/3.63 = 2.25$ times greater than in the case without scatter or uncertainty.

The corresponding annual probability in Case 2 is

$$p_D = 10^{3.3} \times 8.17 \times 10^{-6} = 1.63 \times 10^{-2}$$

and

$$\tau_s = 61.3 \text{ years}$$

Note that the phenomenon is a real one, with the scatter or "uncertainty" coming from physical differences in attenuation from site to site.