A SEISMICITY MODEL FOR NEW ZEALAND

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SYNOPSIS:

A model for the distribution of shallow earthquake magnitudes in and around New Zealand is presented. The model comprises 9 onshore and 8 offshore regions, selected for their general tectonic homogeneity. For each region, values of the Gutenberg and Richter seismicity parameters a and b are estimated using seismological, geological and tectonic data. Smooth transitions between regions are achieved using concepts from fuzzy set theory. The model is well-suited to seismic risk computations.

1. INTRODUCTION:

In this paper we estimate the distribution of seismic activity throughout New Zealand, using seismological, geological and tectonic data. The resulting seismicity model can be used, together with an appropriate attenuation expression, to calculate the risk of damaging ground motion at any site in the country.

The model is based on the instrumental record of earthquakes, and on geological, tectonic and geodetic data. Although the instrumental record⁽¹⁾ of epicentres and magnitudes is the most directly relevant source of seismicity data, its reliability is limited because the seismograph network has only been operating for a short period of time. Geological and tectonic data (which cover much greater time spans, but with less precision) were incorporated into the model as follows to overcome this difficulty. First, the country was divided into 17 regions, each of which is roughly homogeneous in a tectonic sense. Next, initial values of the Gutenberg and Richter seismicity parameters a and b were computed from the post-1944 instrumental record. The large size of each region partly compensates for the shortness of the recording period. Then, finally, the initial a and b values were adjusted according to the number of large earthquakes observed since European settlement, and according to the activity implied by geological and geodetic observations of crustal deformation rates.

Since deep earthquakes are unlikely to cause damage to engineering structures, attention is focussed on shallow earthquakes with hypocentral depths of 50 km or less.

2. FORM OF THE SEISMICITY MODEL:

The seismicity model may be written as a rate function of the following form:

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$$\Lambda = \Lambda(x, y, m) \quad (1)$$

where Λ is the average number of earthquakes per unit area of magnitude m or greater and depth less than 50 km which occur in one year at a location of latitude x and longitude y . (1000 km² is taken as the unit of area).

A more complete description of the seismicity may include the distribution of depths, fault plane orientations and stress drops, but such a description was not adopted because:

- (i) more complete descriptions of earthquake sources are only available for a few earthquakes and,
- (ii) the dependence of ground motions on data such as hypocentral depth and fault plane orientation is not fully understood at present, so such additional information about the source would be of little use.

Guided by the well-known recurrence relation of Gutenberg and Richter⁽²⁾, let us assume that the function $\Lambda(x, y, m)$ takes the following form:

$$\Lambda(x, y, m) = \sum_{i=1}^n \mu_i(x, y) a_{4i} 10^{b_i(4-m)} \quad (2)$$

where each of the n terms represents a separate source. Sources may overlap. Within each source it is assumed that the distribution of magnitudes follows the Gutenberg and Richter recurrence relation. The problem of estimating $\Lambda(x, y, m)$ reduces to that of finding suitable values of the functions of position $\mu_i(x, y)$ and the parameters a_{4i} and b_i .

3. INTERPRETATION OF THE FUNCTIONS $\mu_i(x, y)$ AS FUZZY EQUIREGIONS:

New Zealand seismicity is not confined to fault lines, as in the western United States. Instead it is spread over most of the country with various levels of

(*) The Gutenberg and Richter recurrence relation states that the average number of earthquakes N of magnitude m or greater over a given period of time in a given region may be written as $\log N = a - bm$, where a and b are constants, which are specific to the region.

activity⁽²⁾. One way of modelling this would be to assume that the seismicity is uniform in each of a number of regions. To express this assumption in terms of equation (2) the functions $\mu_i(x,y)$ would be taken as follows:

$$\mu_i(x,y) = \begin{cases} 1 & \text{if } (x,y) \text{ is in region } i \\ 0 & \text{if } (x,y) \text{ is not in region } i \end{cases} \quad (3)$$

Substituting equation (3) into equation (2) gives the following result:

$$\Lambda(x,y,m) = a_{4k} 10^{b_k(4-m)} \quad (4)$$

where k is the number of the region containing the point (x,y) . In this case a_{4k} is the average number of earthquakes of magnitude 4 or greater per 1000 km² per year, and b_k is the constant b in the Gutenberg and Richter recurrence relation.

The disadvantage of dividing the country into equiseismic regions is that it results in very sudden changes in seismic activity at region boundaries. Such sudden changes do not agree with the way the real distribution of seismic activity is expected to behave nor with the seismologist's uncertain notion of where exactly the regional boundaries should be. In this study the idea of equiseismic regions is retained but the boundaries are fuzzified by appropriate choice of the functions $\mu_i(x,y)$. This is done by interpreting $\mu_i(x,y)$ as the degree of membership of point (x,y) to region i .^{*} In addition the following constraint was introduced:

$$\sum_{i=1}^n \mu_i(x,y) = 1 \text{ for any } (x,y) \quad (5)$$

which ensures that if, for example, two regions have the same level of activity, the activity in the boundary zone will equal the activity in either of the two regions.

Figure 1 shows contours for the functions $\mu_i(x,y)$ (degrees of membership to region i). Dotted and continuous lines correspond to degrees of membership of 0.2 and 0.8 respectively. Degrees of membership were assigned at grid points spaced at half a degree in latitude and longitude, and interpolated by assuming linear variations in the North-South and East-West directions.^{**}

4. CRITERIA FOR THE CHOICE OF SEISMIC REGIONS:

4.1 Tectonic Regime -

The boundary between the Pacific and Indian Plates runs in a more or less straight line between Fiordland and East Cape, and

defines a band of high seismicity referred to as the Axial Tectonic Belt⁽⁴⁾. The motion of the Pacific Plate with respect to the Indian Plate is approximately eastwards at a rate of about 40-50 mm per year^(5,6), giving rise to compression and dextral shear along the plate boundary.

Along the east coast of the North Island the Pacific Plate is being subducted beneath the Indian Plate, resulting in a slab of high seismicity, which dips northeastwards at about 50°⁽⁷⁾.

In Fiordland the pattern is reversed, the Indian Plate being subducted beneath the Pacific Plate. The seismic activity is vigorous in both these subduction zones, but the portion of the plate boundary between these zones is remarkably quiescent.

4.2 Regional Characteristics -

In the following, typical characteristics which justified the choice of each region are listed. See Figure 1 for the geographical extent of each region.

Region 1: Main Seismic Region

The Pacific Plate is being subducted along the length of this region. It is the strip along which the slab of high seismicity referred to above intersects the surface.

Distinguishing geological features are the presence of a system of parallel transcurrent faults running in the northeast-southwest direction^(*). For most of these faults there is evidence of post-glacial activity^(8,9,10,11). The hypothesis of Walcott⁽⁴⁾ is that the tangential component of relative plate motion is taken up by shear along the transcurrent faults and the compressional component is taken up by slip along the subduction interface.

This region extends as far south as the southern end of the Hikurangi Trench, which is taken to be the structural feature indicating subduction. At this point there are slight bends in the Awatere, Clarence and Hope faults, and larger fault throws seem to have occurred further to the south as these faults converge to the Alpine Fault.

Although in the last 15 years^(**) the seismic activity in the region between Gisborne and Napier has been more vigorous than in the rest of region 1, large earthquakes have occurred throughout this region since 1840, and for this reason the recent high activity in the Napier-Gisborne area is assumed to be temporary. Possibly it is caused by loss of normal stress on transcurrent faults due to "unlocking" of the subduction interface during the 1931 Napier Earthquake. (Walcott⁽⁴⁾ and pers. comm.).

(**) Since 1964, 15 years ago, the record of instrumentally recorded earthquakes is thought to be complete for magnitudes 4 or greater.
(*) Examples are the Wairau, Awatere, Clarence and Hope faults in the South Island, and the Wellington and Wairarapa faults in the North Island.

*The use of "fuzzy equiseismic regions" was inspired by the fuzzy set theory of Zadeh³.

**Tables of values of μ_i can be requested from the second author.

Region 2: Taupo Volcanic Zone -

The geology of this region is characterized by active volcanism and the presence of a system of parallel active faults running in the northwest-southeast direction between Lake Taupo and the Bay of Plenty. It seems⁽¹²⁾ that crustal extension is occurring, the faults mentioned being the result of failure in vertical compression due to the loss of horizontal confining stresses associated with crustal extension^(**).

A possible way of explaining crustal extension in a regime of plate convergence is to attribute it to flexure of the crust.

The seismicity is shallow, and a high b-value is obtained from the assigned magnitudes of instrumentally recorded earthquakes of the past 15 years.

It is not surprising that the seismicity of this region should exhibit some special characteristics because:

- (i) If flexure of the crust is occurring the stress will vary across the thickness of the crust and the critically stressed regions will be smaller.
- (ii) "Tensile" failure of rock, or rather failure due to lack of horizontal confining stresses occurs at lower stress levels and therefore is likely to be less violent.
- (iii) It is possible that thermally induced strains are of some importance. In any case the temperature of rock will influence its properties.

Region 3: Tasman Zone -

There is little geological information about this region, except that tertiary sediments extend to large depths.

As for Region 2, the seismicity over the last 15 years shows a high b-value.

Region 4: Northland -

According to Lensen⁽¹³⁾ bedding planes of miocene age are still found untilted here implying that no crustal deformation is occurring. The seismic activity is extremely low.

Region 5: Taranaki - Waikato -

There is little evidence of active faulting in this region⁽¹⁵⁾. Structures such as the Hauraki Graben indicate crustal extension⁽¹²⁾. The seismic activity is moderate with a high b value in the last 15 years (1964-1979). Hence the tectonic as well as the geological

(**) At a depth of 12km, which is typical for a shallow earthquake, the overburden pressure is about 3 kilobars (300 MPa) - well above the unconfined compressive strength of most rocks⁽¹⁴⁾.

characteristics of this region suggest that it represents a transition zone between regions 2 and 4.

Region 6: Inangahua Region -

Geologically, this region is distinct from region 1 in that reverse faulting occurs, indicating crustal compression. Seismically the activity has been extremely vigorous in the last 15 years. Although some recorded earthquakes may merely be aftershocks of the 1968 Inangahua Earthquake, three earthquakes of magnitude 7 or greater have been observed here since 1929.

Region 7: The Alpine Fault -

This region consists of locations within 20 km of the Alpine Fault trace.

Seismically the Alpine Fault has been remarkably quiescent since 1840, but there is geological evidence indicating some 75 m of fault throw over the last 8000 years (9.3 mm/yr)⁽¹⁶⁾.

In addition, from dated landslides, Adams⁽¹⁶⁾ found that some landslides at different locations had occurred at the same time. He concluded that they had been triggered by earthquakes and was able to estimate a return period of 500 years for earthquakes of magnitude about 8.

Region 8: Canterbury/Otago -

According to Lensen⁽¹²⁾ this is a region of crustal compression with "secular horizontal deformation rates" decreasing eastwards. Since seismic activity showed a similar trend, the degree of membership to region 8 was also taken to decrease slowly eastwards.

Region 9: Fiordland -

Subduction of the Indian Plate is thought to be occurring here. As in region 1 (where the Pacific Plate is being subducted) the seismicity is vigorous, especially over the last 15 years.

Region 10:

From the recorded seismic activity this region seems to be a continuation of the Fiordland Region⁽⁹⁾.

Regions 11 to 17:

Except for region 14, the Kermadec Trench Region, these regions are practically aseismic and of little interest to seismic risk evaluation.

5. ESTIMATION OF THE REGIONAL PARAMETERS a_{4i} and b_i :

The parameters a_{4i} and b_i characterise the seismicity of each region. a_{4i} is the number of earthquakes with $M > 4$ occurring on the average per unit area (1000 km²) per year and b_i gives the rate of decay of the frequency of

occurrence of earthquakes with increasing magnitude. The data used to estimate a_{4i} and b_i are the following:

- (a) The record of earthquakes detected by the New Zealand network of Seismographs(1). This record is considered complete for earthquakes of magnitude 4 or greater since 1964, and for earthquakes of magnitude 5 or greater since 1944 (Smith pers. comm.). The magnitudes have been determined accurately enough to be of use in estimating b-values.
- (b) The historical record of large earthquakes felt since 1840. These are shown in Figure 2 and are listed in Tables 2 and 3. The completeness and accuracy of this record depends on whether the region was populated from 1840.
- (c) Earth deformation data. These include:
 - . geological data enabling an estimation of the rate of movement on a fault;
 - . tectonic plate motion rates obtained from data on sea-floor spreading, and information on the kinematics at the plate boundary;
 - . geodetical shear strain rates.
 (It is noted that geological, tectonic and morphological information has already been used in a qualitative way in the choice of the seismic regions).

In the following, a numerical method for calculating a_{4i} and b_i from a complete record of earthquake magnitudes and epicentral locations is developed. Then the parameters a_{4i} and b_i are computed from earthquakes of magnitude 4 or greater since 1964 and for earthquakes of magnitude 5 or greater since 1940. Finally, the results are compared and modified in the light of earth deformation data and historical earthquakes.

5.1 The Computation of the Regional Seismicity Parameters a_{4i} and b_i from a Complete Set of Well-Recorded Earthquakes -

Assume that during a time interval Δt the magnitudes m and epicentral coordinates x and y have been determined for all earthquakes of magnitude 4 or greater and depth less than 50 km. Or formally, data points of the form

$$(x_j, y_j, m_j) \quad j = 1, 2, \dots, \hat{m}$$

are available, where $\hat{m}$ is the total number of earthquakes of magnitude 4 or greater that have occurred in time Δt .

Consider the seismicity distribution expressed by equation 2 as superposition of earthquake sources, each of which produces earthquakes at a certain rate depending on magnitude and location.

Assume that any earthquake (x_j, y_j, m_j) originates from one source only. Then, since the sources are overlapping in space, it is not possible to determine from which source an observed earthquake originated. However, from the relative rates of occurrence of earthquakes in each of the overlapping sources, the probability P_i that an earthquake of description (x, y, m) originated from source i may be found as follows:

The rate of occurrence of earthquakes of description (X, Y, M) satisfying

$$\begin{aligned} x < X < x + dx \\ y < Y < y + dy \\ m < M < m + dm \end{aligned} \quad (6)$$

and originating from source i is:

$$r_i = \mu_i(x, y) a_{4i} \ln(10) b_i 10^{-b_i(m-4)} dx dy dm \quad (7)$$

(This is obtained from the i^{th} term of equation (2)).

The probability $P_i(x, y, m)$ is the ratio of the rate of occurrences of earthquakes of description (6) originating from source i to the total rate of occurrences of earthquakes of the same description, (6). That is:

$$P_i(x, y, m) = \frac{r_i}{\sum_{k=1}^n r_k} \quad (8)$$

Substituting equation (7) into equation (8) gives

$$P_i(x, y, m) = \frac{\mu_i(x, y) a_{4i} b_i 10^{-b_i(m-4)}}{\sum_{k=1}^n \mu_k(x, y) a_{4k} b_k 10^{-b_k(m-4)}} \quad (9)$$

If n_e earthquakes (x_j, y_j, m_j) are observed, the expected number of earthquakes which originated from source i is

$$\sum_{j=1}^{n_e} P_i(x_j, y_j, m_j) \quad (10)$$

Now the average number of earthquakes of magnitude 4 or greater which are produced by source i in time Δt is

$$\begin{aligned} \Delta t \iint_{\text{Area}} \mu_i(x, y) a_{4i} b_i 10^{-b_i(4-4)} dx dy \\ = \Delta t A_i a_{4i} \end{aligned} \quad (11)$$

$$\text{where } A_i = \iint_{\text{Area}} \mu_i(x, y) dx dy \quad (12)$$

A_i will be referred to as the area of region i .

TABLE 1 : ESTIMATION OF SEISMIC ACTIVITY PARAMETERS a_{4i} AND b_i

Region Number <i>i</i>	(1) Area <i>A_i</i> × 1000 km ²	<i>a_{4i}</i> and <i>b_i</i> computed from instrumental records										(6) tentative <i>a_{4i}</i> & <i>b_i</i> (instrumental)	(7) <i>N_{6.5}</i> (certain)	(8) <i>N_{6.5}</i> (certain)	(9) <i>N_B</i>	(10) <i>N_{6.5}</i> (historical)	(11) <i>M_o</i> × 10 ²⁵ dyne cm per yr	(12) <i>N_{6.5}</i> (geological)	(13) <i>a_{4i}</i> & <i>b_i</i> used		(14) <i>N_{6.5}</i> (final)
		(2) <i>M</i> > 4 1964-1979		(3) <i>M</i> > 5 1944-1964		(4) av. of (2) & (3)		(5) <i>M</i> > 5 1944-1979		(13) <i>a_{4i}</i> & <i>b_i</i> used											
		<i>a_{4i}</i>	<i>b_i</i>	<i>a_{4i}</i>	<i>b_i</i>	<i>a_{4i}</i>	<i>b_i</i>	<i>a_{4i}</i>	<i>b_i</i>	<i>a_{4i}</i>	<i>b_i</i>										
		<i>a_{4i}</i>	<i>b_i</i>	<i>a_{4i}</i>	<i>b_i</i>	<i>a_{4i}</i>	<i>b_i</i>	<i>a_{4i}</i>	<i>b_i</i>	<i>a_{4i}</i>	<i>b_i</i>										
1	110.85	0.552	1.193	0.401	1.095	0.510	1.187	0.453	1.103	0.500	1.100	13.80	13.35	16.2	17.6	35.00	16.0	0.575	1.098	16.0	
2	20.77	0.517	1.429	0.174	1.132	0.203	1.395	0.183	1.184	0.200	1.280	0.37	0	1.6	.37	2.49	1.14	0.200	1.250	0.436	
3	50.88	0.089	1.73*	0.232	1.44*	0.207	1.44*	0.185	1.44*	0.220	1.200	1.57	2.5	7.4	4.26	9.15	4.18	0.253	1.100	3.2	
4	56.24	0.001	1.04*	0.008	1.00*	0.002	1.00*	0.005	1.00*	0.004	1.000	0.01	0	0.0	0			.005	1.00	0.12	
5	32.11	0.113	1.493	0.081	0.935	0.094	1.354	0.084	1.214	0.100	1.200	0.45	0.35	1.5	.61	5.77	2.63	0.11	1.164	0.61	
6	12.11	1.477	1.146	0.441	1.45*	0.770	1.150	0.576	1.042	0.670	1.100	2.01	2.3	0.5	2.4	3.27	1.49	0.67	1.100	2.02	
7	10.69	0.255	1.067	0.502	1.45*	0.238	1.122		0.238	1.122	1.122	0.55	0.4	0	0.4	3.74	1.71	0.240	0.90	2.00	
8	79.80	0.051	1.019	0.142	0.833	0.098	0.943	0.076	1.106	0.090	0.940	4.49	0.5	4.2	1.8	3.80	1.74	0.09	1.10	1.74	
9	23.66	1.059	0.950	0.204	1.147	0.791	0.949	1.034	1.412	0.600	0.980	7.05	2.0	0	2.0	12.83	5.68	0.500	0.980	5.86	
10	28.75	0.334	0.878	0.104	0.725	0.192	0.862	0.235	0.904	0.200	0.870	5.38						0.200	0.870		
11	209.72					0.003	0.805											0.003	0.805		
12	160.80					0.142	1.281											0.142	1.281		
13	218.27					0.00	1.04*											0.000	1.00		
14	104.98					0.310	0.998											0.310	0.998		
15	101.95					0.010	1.168											0.005	1.00		
16	613.25					0.003	1.127											0.005	1.00		
17	197.46					0.017	0.876											0.020	0.950		

* These b-values were assigned because there were not enough data, or the computed b-values were too large

TABLE 2 : FELT EARTHQUAKES FROM 1840 TO 1979 TO WHICH MAGNITUDES OF 6.5 OR GREATER WERE ASSIGNED

Year	Epicentral coordinates		Magnitude M	Probabilities that the earthquake originated from each source (estimated from Figure 2, and tentative source activity parameters in Table 1, col. 6)										Name of Earthquake
	lat. (°S)	long. (°E)		1	2	3	4	5	6	7	8	9	Other source	
1843	39.9	175.0	7.5	.05	.95									Wanganui
1848	41.5	173.8	7.1	1										Marlborough
1853	39.0	174.0	6.5		.65	.35								-
1855	41.5	175.2	8	1										South-West Wairarapa
1888	43	172	7	.5						.5				North Canterbury
1897	40	175	7	.1	.3							.1		-
1904	40.5	177	7.5	.9										East Coast
1914	38	178	7	1										-
1914	38	178	6.5	1										-
1929	42.5	172	6.9	.3					.3	.4				Arthur's Pass
1929	41.8	172.2	7.7						1					Buller
1931	39.3	176.7	7.7	1										Hawkes Bay
1931	39.3	176.7	6.5	1										-
1931	39.3	176.7	7.1	1										-
1932	38.9	177.55	7	1										Wairoa
1934	40.5	175.6	7.5	1										Pahiatua
1942	40.9	175.9	7.0	1										Wairarapa
1943	46.1	167.0	6.7	.5						.5				-
1943	36	177	6.8							1				-
1947	39.7	179.2	6.7							1				-
1947	44.2	169.0	6.6						.4	.6				-
1951	37.8	178.2	6.7	1										-
1957	44.5	166.0	6.6							1				-
1960	44.2	167.7	7.0			.4			.6	.4				Fiordland
1968	41.77	172.01	7.1					1						Inangahua
1968	46.71	166.78	6.5							1				-
1976	44.68	167.46	7.0								1			Milford Sound
Sums = $N_{6.5}$ (certain)				13.35	0	2.5	0	.35	2.3	.4	.5	2	5.6	

TABLE 3 : FELT EARTHQUAKES SINCE 1840 WHICH HAVE BEEN CLASSIFIED AS MAGNITUDE CLASS B. (MAGNITUDES 6.5 TO 7.5)

Year	Epicentral coordinates		class	Probabilities that the earthquake originated from each of the sources (estimated by inspection of Figure 2 and tentative source parameters in Table 1, col. 6)										Name of earthquake
	lat. (°S)	long. (°E)		1	2	3	4	5	6	7	8	9	Other source	
1846	47	168	B										.1	.9
	41	172	B			.5			.5					
	41.0	174.5	B		.6	.4								
1848	41	175	B	1.0										
	41.5	173.8	B	1.0										
	41.5	173.8	B	1.0										
	41.5	173.8	B	1.0										
	41	174	B	.2	.8									
1851	41	173	B		1.0									
1855	41.5	175.2	B	1.0										
	41.5	175.2	B	1.0										
1863	39.5	177	B	1.0										
1868	39	174	B		.5	.5								
	40	174	B		1.0									
1876	45	171	B									1.0		
1881	43	172	B									1.0		
1888	43	172	B									1.0		
1891	37.4	174.5	B					1.0						
1893	41	173	B			1.0								
1895	39	176	B		.8	.2								
1901	43	173.5	B	.3								.3	.4	
1917	40.8	176.0	B	.9									.1	
1922	39	176	B	.8	.2									
	43	173	B	.1								.8	.1	
1925	42	174	B	1.0										
1928	40	174	B		1.0									
	44	170	B										1.0	
1929	40	175	B	.2	.8									
1930	40.9	177.1	B	.9									.1	
1931	39.5	176.9	B	1.0										
	37.0	178.0	B	1.0										
1932	39.5	177.6	B	1.0										
	40.0	174.0	B	1.0										
1938	40	177	B	1.0										
Sums = N_B				16.2	1.6	7.4	0	1.5	.5			4.2	2.6	

To determine the parameters a_{4i} (if b_i are known) the mean number of earthquakes produced by source i (expression 11) is equated to the expected number of observed earthquakes which originated from source i . (expression 10). This gives

$$a_{4i} = \frac{1}{A_i \Delta t} \sum_{j=1}^{n_e} P_i(x_j, y_j, m_j) \quad (13)$$

or, substituting (9) into (13)

$$a_{4i} = \frac{1}{A_i \Delta t} \sum_{j=1}^{n_e} \frac{\mu(x_j, y_j) a_{4i} b_i 10^{-b_i(m_j-4)}}{\sum_{k=1}^n \mu(x_j, y_j) a_{4k} b_k 10^{-b_k(m_j-4)}} \quad (14)$$

Equations (14) are a set of n equations from which the parameters a_{4i} may be determined by re-evaluating the right hand side of equation (14) until satisfactory convergence is achieved.

So far it has been assumed that b_i are known. In fact b_i may be estimated from seismological data by using the method of maximum likelihood⁽¹⁷⁾. This gives

$$b_i = \frac{\log_{10}(e)}{\bar{M}_i - 4} \quad (15)$$

where $\bar{M}_i$ is the average magnitude of earthquakes of magnitude 4 or greater originating from source i . Since the earthquakes originating from source i are not identified it is necessary to use the following approximation for $\bar{M}_i$:

$$\bar{M}_i = \frac{\sum_{j=1}^{n_e} m_j P_i(x_j, y_j, m_j)}{\sum_{j=1}^{n_e} P_i(x_j, y_j, m_j)} \quad (16)$$

where $P_i(x, y, m)$ is as given by equation (9). The following iterative procedure was used to evaluate parameters a_{4i} and b_i :

a) put $a_{4i} = 1$ and $b_i = 1$ for all i

b) evaluate

$$\sum_{j=1}^{n_e} P(x_j, y_j, m_j)$$

and

$$\sum_{j=1}^{n_e} m P(x_j, y_j, m_j)$$

by using equation (9)

c) calculate new a_{4i} from equation (13) and calculate new b_i from equations 15) and (16)

d) repeat steps (b) and (c) until satisfactory convergence is achieved.

(5 iterations were found to be sufficient).

These computations were carried out for

i) All earthquakes of magnitudes 4 and greater from 1964 to 1979. (See Table 1, column 2)

ii) All earthquakes of magnitude 5 or greater from 1944 to 1964. (Table 1, column 3)

iii) An average of (i) and (ii). Table 1, column 4)

iv) All earthquakes of magnitudes 5 and greater from 1944 to 1979.

It can be seen from Table 1, col 5, that the parameters a_{4i} and b_i vary considerably. This occurs because over a short period of 15 to 35 years aftershocks of large earthquakes and swarms may severely affect the average recorded seismicity and the magnitude distribution. Hence these results must be taken as indications subject to modification in the light of historical seismicity and geological evidence.

5.2 Adjustment of Regional Activity Parameters -

The seismic activity parameters a_{4i} and b_i from instrumental data of the last 35 years were modified by the following procedure:

1) From the results shown in Table 1, cols. 2,3,4,5 tentative values for a_{4i} and b_i were estimated (Table 1, col. 6).

2) Using the values of a_{4i} and b_i estimated in (1) the number of earthquakes exceeding magnitude 6.5 expected to have occurred since 1840 was calculated as

$$N_{6.5}(\text{instrumental}) = 140 a_{4i} 10^{-b_i(2.5)}.$$

These values appear in Table 1, col. 7.

3) The expected number of felt earthquakes of magnitude 6.5 or greater to have originated from each source since 1840 was estimated as

$$N_{6.5}(\text{historical}) = N_{6.5}(\text{certain}) + N_B P(M > 6.5 | \text{Class B}),$$

where

$$N_{6.5}(\text{certain}) = \text{expected number of the earthquakes which were assigned}$$

a magnitude of 6.5 or greater to have originated from each source. For a particular source $N_{6.5}$ (certain) was determined by using Figure 2, and the tentative source activities to estimate the probability that each earthquake originated from the source considered and summing these probabilities (see Table 2).

N_B = expected number of earthquakes which were assigned magnitude class B by Eiby⁽¹⁸⁾ to have originated from each source. The determination of N_B follows the same procedure used to determine $N_{6.5}$ (certain) and is shown in Table 3.

$P(M > 6.5 | \text{Class B})$ = the probability that an earthquake which Eiby classified as class B was of magnitude 6.5 or greater. It can be shown that, if magnitude class B comprises all earthquakes of magnitude between 6.0 and 7.5, and the Gutenberg and Richter recurrence relation applies, this probability is

$$P(M > 6.5 | \text{Class B}) = (10^b - 1) / (10^{1.5b} - 1).$$

$N_{6.5}$ (certain), N_B , and $N_{6.5}$ (historical) are shown in Table 1, cols. 8, 9 and 10 respectively.

- 4) The rate of release of seismic moment M_0 was estimated using the techniques of Anderson⁽¹⁹⁾ and Molnar⁽²⁰⁾ for each region, by using geological, tectonic and geodetic data. (Table 1, col.11). Details of the computations are given by Peek⁽²¹⁾.
- 5) New values of $N_{6.5}$ denoted $N_{6.5}$ (geological) were determined by assuming that M_0 is proportional to $N_{6.5}$ and evaluating the constant of proportionality by assuming that for region 1 $N_{6.5}$ (geological) = 16.0 (Table 1, col.12).
- 6) By comparing the values of $N_{6.5}$ (instrumental), $N_{6.5}$ (historical) and $N_{6.5}$ (geological) new values of parameters a_{4i} and b_i were chosen (Table 1, col. 13).
- 7) $N_{6.5}$ was recalculated (Table 1, col.14) for comparison, and the choice in (6) modified where appropriate.

5.3 Specific notes on the a_{4i} and b_i values chosen

Region 1 -

$N_{6.5}$ (instrumental) = 13.8 and $N_{6.5}$

(historical) = 17.6 are in good agreement. The parameters a_{4i} and b_i were adjusted so as to give $N_{6.5}$ (final) an intermediate value of 16. This value was used to calculate the constant of proportionality relating to M_0 to $M_{6.5}$ (geological).

Region 2 -

$N_{6.5}$ (geological) = 1.14 is higher than $N_{6.5}$ (instrumental) = 0.37 by a factor of 3.08. Some possible explanations are:

- i) The Taupo earthquake swarm of 1964-1965 may have caused some bias in the computed b values, especially those for 1964-1979 and $M > 4$ (Table 1, col. 2). This bias resulted in a high computed b value and lead to the low value of $N_{6.5}$ (instrumental).
- ii) According to Gibowicz and Hatherton⁽²²⁾, this is a region of small displacements, which means that the magnitude for a given seismic moment is small. (Small displacements are to be expected since in their model displacements are approximately proportional to stress drops, which are themselves small due to the generally tensile nature of the region).

Hence $a_{42} = 0.200$ and $b_2 = 1.250$ seemed a reasonable choice.

Region 3 -

Taking $b_3 = 1.100$ and $a_{43} = 0.253$ is thought to be a reasonable compromise between the instrumental a_{43} value, which indicates lower activity and the values of $N_{6.5}$ (historical) and $N_{6.5}$ (geological), which indicate a higher activity. Although the good agreement between $N_{6.5}$ (geological) and $N_{6.5}$ (historical) suggests that more weight should be given to these, this was not done because the estimate of $N_{6.5}$ (geological) was based on very scanty information.

Region 4 -

Very low activity also means very little information. Assuming the seismicity is similar to that of regions 15 and 16 leads to the choice of $a_{44} = 0.005$ and $b_4 = 1.00$. These values were also adopted for regions 15 and 16.

Region 5 -

For the same reasons given for Region 2, it is likely that $N_{6.5}$ (geological) is too high. Hence more weight was given to historical and instrumental data resulting in the choice of $a_{45} = 0.110$ and $b_5 = 1.164$.

Region 6 -

$a_{46} = 0.670$ and $b_6 = 1.100$ is taken

mainly from instrumental data. It is noted that $N_{6.5}$ (geological) was estimated from the geodetic shear strain rate, which ignores the effect of compression or dilation.

Region 7 -

M_0 was calculated by assuming that only 30% of the estimated rate of movement on the Alpine Fault occurs during earthquakes. This lead to $N_{6.5}$ (geological) = 1, which is not irreconcilable with the fact that no event of magnitude 6.5 or greater has been observed on the Alpine Fault. However Adams(16) estimates a return period of 500 years for earthquakes of magnitude about 8. If $b = 0.9$ is assumed this would mean that $N_{6.5} = 2.2$. As a suitable compromise $a_{47} = 0.24$ and $b_7 = 0.9$ was chosen, which leads to $N_{6.5}$ (final) = 2.0.

Region 8 -

$N_{6.5}$ (geological) = 1.74 and $N_{6.5}$ (historical) = 1.8 are in good agreement. Instrumental data indicate that $a_{48} = 0.09$, but leave some doubt what the b value should be. The b value to match $a_{48} = 0.09$ and $N_{6.5} = N_{6.5}$ (geological) = 1.74 is $b_8 = 1.10$.

Region 9 -

Smith(23) points out that due to the sparsity of population in this region, the historical record of earthquakes since 1840 is probably incomplete. Hence the value of $N_{6.5}$ (historical) may be disregarded. Taking $a_{49} = 0.500$ and $b_9 = 0.980$ gives $N_{6.5}$ (final) = 5.86, which is considered a reasonable average from $N_{6.5}$ (instrumental) and $N_{6.5}$ (geological).

Regions 10 to 17 -

Little historical and no geologic information is available for the offshore regions 10 to 17, hence values of a_i and b_i were chosen from the instrumental seismicity record above. This should not affect the final results since these regions have little influence on seismic risk on land. However, it is worth noting that the $N_{6.5}$ values per unit area for the two most active regions, 10 and 14, agree closely with those of their tectonically-related neighbouring regions, 9 and 1 respectively.

6. CONCLUSIONS:

A wide range of information comprising geological, tectonic, seismological and geodetic data have been used to estimate the distribution of seismic activity in New Zealand.

The seismicity model presented here can be combined with an attenuation model, relating intensity of shaking at a

site to earthquake magnitude and location, to compute the risk of damaging ground motion at a site(21,24). This has been done in an exploratory manner for New Zealand by Peek(21), using a Japanese attenuation expression. However, because of the high sensitivity of the results to details of the attenuation expression, the authors consider that further research into attenuation models relevant to New Zealand crustal conditions is necessary before such results are adopted for general use.

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