Effects of Regional Geology on the Seismic Hazard in Christchurch, New Zealand

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SUMMARY A detailed seismic hazard assessment has been carried out for Christchurch, New Zealand. A seismicity model has been developed for the central South Island. The effects of very deep alluvial soils beneath the city have been evaluated. The overall seismic hazard is considerably greater than has previously been thought.

1. INTRODUCTION

Several comprehensive seismic hazard assessments have previously been carried out for New Zealand (e.g. Smith & Berryman, 1983; Matuschka et al, 1985). Although these studies were necessarily on a coarse scale and took only nominal account of regional geology-related factors such as fault seismicity or attenuation pattern variations, they have often been used to estimate the earthquake hazard at Christchurch.

Evidence from recent geologic studies indicates that a number of fault zones in the central South Island, including the Alpine Fault and others in North Canterbury, have the potential to generate larger earthquakes than has previously been assumed (e.g. Cowan & Pettinga, 1990). In addition, seismic hazard assessments for specific sites in Christchurch, employing all available geotechnical information for those sites (Soils & Foundations, 1988) suggest that earthquake effects in some areas of the city would be considerably stronger than at comparable epicentral distances from similar earthquakes in other areas of New Zealand. Brown et al (1991) confirmed the severity of the earthquake hazard for the city from a qualitative evaluation of Christchurch geology.

Examination of these recent research results highlighted the urgent need for a comprehensive evaluation of the seismic hazard in Christchurch. The results of this evaluation are reported in detail by Elder, McCahon & Yetton (1991).

Damage to structures at a given epicentral distance during a particular earthquake varies with ground conditions at different locations. Ground shaking is usually most severe on geologically recent, loose or soft sedimentary deposits. Notable examples of earthquakes where strong localised magnification occurred on these types of soils are the 1985 Mexico City earthquake and the 1989 Loma Prieta (San Francisco) earthquake.

In general the effects of an earthquake with magnitude M = 8.1 at 400 km epicentral distance (i.e. Mexico City during the 1985 earthquake) could also be generated by a smaller earthquake with M = 7.0 at 100 - 150 km or M = 7.5 at 50 - 100 km. A number of fault zones in the central South Island would satisfy these criteria for generation of effects at Christchurch. Furthermore, the Alpine Fault, within 125 km of Christchurch at its nearest point, and relatively quiescent during the past 150 years, is estimated to have experienced at least four large earthquakes ($M \geq 8$) at intervals of about 500 - 550 years. The last such event was about 550 years ago.

The quaternary alluvial deposits of loose, cohesionless soils beneath Christchurch are stiffer (but far deeper) than the soft clays beneath critically affected areas of Mexico City. In many places these soils are similar to the loose sands and silts in the Marina District of San Francisco. This great depth of uncemented soils beneath Christchurch (up to 1 km) enhances the potential for amplification of incident seismic waves due to impedance mismatches and constructive interference at soil strata boundaries.

The expected amplification of effects at Christchurch is supported by past observations. During a number of historical earthquakes, higher intensities have been reported at Christchurch than at other locations equidistant from the epicentre but on bedrock or shallow soils (Elder, McCahon & Yetton, 1991). Dibble et al (1980) concluded from historical evidence that intensities at Christchurch were, **on average**, 0.9 MM units higher than at Lyttelton and 1.6 MM units higher than at Akaroa. In some parts of the city intensities were more than 2 MM units higher than on Banks Peninsula.

Studies by Dibble et al (1980) and Davis & Berrill (1988) showed that Christchurch can expect significant frequency-dependent amplification of spectral accelerations. These would not be accounted for adequately either by the allowance for 'soft soil' effects made in the current New Zealand Design Loadings Code, or by existing spectral generation models.

2. ANALYSIS TECHNIQUES

Seismic hazard analysis requires use of a seismicity model to describe the rate of occurrence of earthquakes of different magnitude in each source region, and an attenuation model to describe the ground shaking effect produced at a site away from the source. Some attenuation models allow for variable site geology by using simplified groupings of ground characteristics, however to accurately predict effects at specific sites it is generally necessary to employ separate, additional analyses.

The seismic hazard analysis for New Zealand reported by Smith & Berryman (1983) estimated intensities using three different attenuation models for different areas of the country. No site-specific effects were included in the model, which predicted return periods at Christchurch:

Intensity (MM units)	Return Period
VI	14 years
VII	48 years
VIII	160 years
IX	600 years

The study reported by Matuschka et al (1985) estimated spectral accelerations throughout the country using a modified version of the attenuation model proposed by Katayama (1982). A slightly different attenuation model was used for each of four Ground Class conditions to make some allowance for site geology. Spectral accelerations predicted at Christchurch for structure natural period T = 0.2 seconds (close to peak structural response for the attenuation models used) were:

a_s	Return Period
0.3g	50 years
0.45g	150 years
0.8g	450 years
1.0g	1000 years

In this study a general source-to-site attenuation model was used to predict the bedrock motion beneath the deep alluvium at Christchurch, then a separate deep soil response model was employed to determine the variable effects throughout Christchurch caused by spatial soil inhomogeneity in the deep alluvium.

3. SEISMICITY MODEL

The seismicity model developed to describe the rate and magnitude of earthquake occurrence in source regions through the central-northern South Island has the mathematical form:

$$N = a_4[10^{b(4-M)} - 10^{b(4-M_{max})}] \qquad (1)$$

where N is the annual number of earthquakes per given area with magnitude $\geq$ M, a_4 is the annual number of earthquakes with magnitude $\geq$ 4, b is a constant and M_{max} is a constraining maximum magnitude. M_{max}, a_4 and b are determined for each characteristic source region. Details of the model are described elsewhere (Elder, McCahon & Yetton, 1991; 1992).

The model bears similarities to that of Smith & Berryman (1983), but a number of significant modifications have been made to improve the accuracy of prediction at Christchurch:

- seven small, new seismicity zones have been employed in north and offshore Canterbury with boundary delineations suggested by recent geologic, tectonic and seismicity evidence
- the seismicity parameter *b*, often assumed to be close to 1.0, is decreased to 0.5-0.8 in some smaller zones to fit seismicity data. These smaller values are consistent with recommendations for medium to large earthquakes on individual faults, or in small, tightly constrained fault zones (e.g. Schwartz & Coppersmith (1986).
- parameters for the Alpine Fault region have been significantly adjusted to best reflect available geologic evidence for large earthquakes
- maximum magnitudes M_{max} have been reduced in regions where very large earthquakes are considered unlikely

4. INTENSITIES PREDICTED AT CHRISTCHURCH

The intensity attenuation model developed by Smith (1978a,b) has been refined to allow for variable directions of energy propagation consistent with tectonic features in the South Island (Elder et al, 1991). To simplify computation, a functional relationship has been developed among magnitude, distance and intensity.

This attenuation relationship is used with the source seismicity model described above to estimate exceedance probabilities for different intensities at Christchurch, fo "average ground" conditions. The "continuous" intensity predicted by the model converts to the "Modified Mercalli intensity by simple truncation (e.g. I=7.3 gives MM VII).

For medium intensities at Christchurch ($6 \leq I \leq 8$) the inferred seismic hazard at Christchurch is contributed to almost evenly by seismicity zones and known faults within 100 km of the city. At higher intensities very large earthquakes in more distant seismicity zones begin to dominate.

Intensities recorded near Christchurch during a number o historical earthquakes were investigated to assess the likely effect of the deep, loose cohesionless soils beneath the city. Isoseismal pattern distortions for a number o these suggest amplification of intensities above levels recorded at Banks Peninsula, where sites are on shallow soil or bedrock. Intensities recorded in Christchurch and on Banks Peninsula are compared in Figure 1 for nineteen historical earthquakes.

For three of these earthquakes, the mean intensities felt a Christchurch were up to one MM unit lower than those felt on Banks Peninsula. For six earthquakes the mean intensities were the same, while for the remaining ten the mean intensities at Christchurch were up to three MM units higher than those reported on Banks Peninsula.

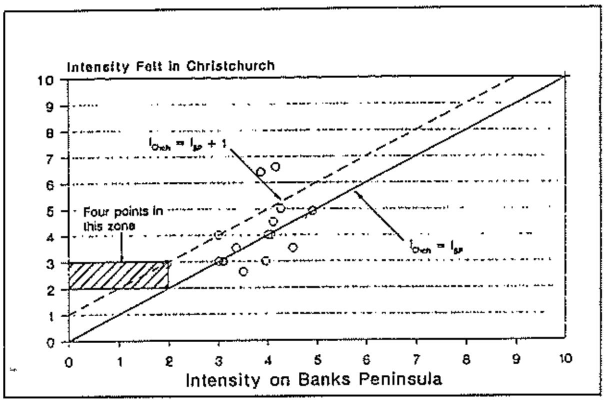


Figure 1. Comparison of Felt Intensities at Christchurch and on Banks Peninsula

Scatter in the comparison is expected due to the different reporting locations for different earthquakes, and variable epicentral distances. However some intensity amplification on Banks Peninsula may also occur due to geometric focusing, or in valleys where deeper soil deposits also coincide with greater population. Although the correlation is not strong, it appears reasonable to assume that intensities felt at Christchurch are, on average, at least 0-1 MM units higher than those for "average ground" at equivalent epicentral distances elsewhere in the country.

Return periods predicted for different intensities at Christchurch, allowing for ground amplification effects, are shown in Figure 2. Intensities predicted by Smith & Berryman (1983) for "average ground" are shown for comparison.

The effect of improving the seismicity model is to decrease the intensities predicted for "average ground" at Christchurch below those predicted by Smith & Berryman for return periods <20 years or >500 years. Intensities with return periods 20-300 years are higher than those predicted by Smith & Berryman.

However intensities at Christchurch are amplified on average by about 1 MM unit above those on "average ground" and then significantly exceed Smith & Berryman's predictions at all return periods. These results suggest that Christchurch is likely to experience medium to high shaking intensities at least as frequently as Wellington. Only for very long return periods (>> 1,000 years) is the predicted intensity higher for Wellington.

5. ACCELERATION RESPONSE SPECTRA

Acceleration response spectra are predicted for "bedrock conditions" at Christchurch using the source seismicity model and the attenuation model of Katayama (1982). A number of modifications proposed for New Zealand conditions (e.g. McVerry, 1986) have been examined in detail (Elder et al, 1991). We consider that at present the justification for their use in New Zealand is not apparent either on the basis of the original data presented, or from analysis of other data. The original Katayama model is consequently used without modification as the best available at present for New Zealand geological conditions.

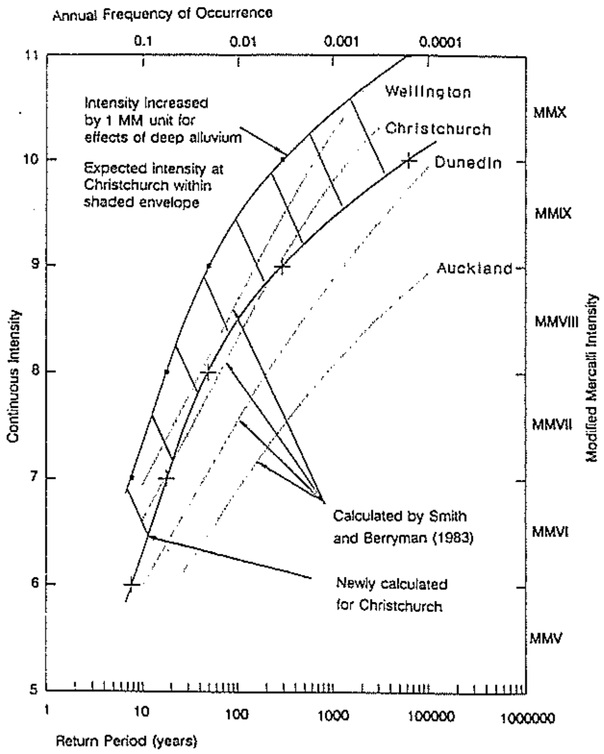


Figure 2. Return Periods for Different Intensities at Christchurch

Analysis of the maximum likely earthquake magnitude in each seismicity zone, and distances from Christchurch, suggests that the most severe effects at the city can not be clearly attributed to any one fault or seismicity zone. Instead, similar effects could be caused by medium sized earthquakes very close to the city; by large, slightly more distant earthquakes or by very large, distant earthquakes. This deterministic approach is useful in comparing the types of acceleration response spectra likely to be generated at Christchurch by each type of earthquake. These typical maximum earthquakes in each seismicity zone may be represented by three examples:

1. M=7.0, r=25km eg.	Porters Pass zone - Ashley section; Canterbury Plains zone; Pegasus zone
2. M=7.3, r=50km eg.	Porters Pass tectonic zone; Banks Peninsula zone
3. M=8.1, r=150km eg.	Alpine Fault

Acceleration response spectra at Christchurch for each of these three earthquakes are shown in Figure 3.

The three spectra shown in Figure 3 are very similar. This confirms that no one or group of zones dominates a deterministic analysis for Christchurch. It also supports previous findings (e.g. Mulholland, 1982) that a relatively uniform spectral shape can be assumed throughout New Zealand, independent of location or return period.

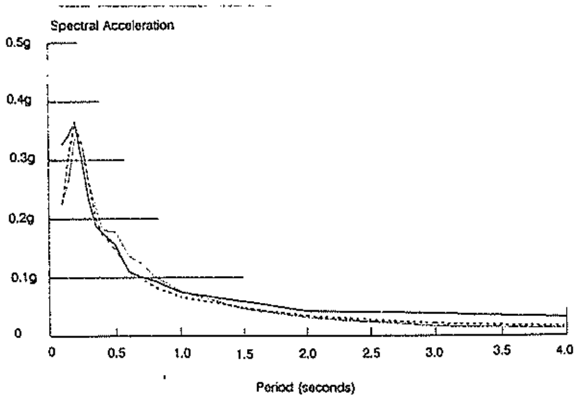


Figure 3. Typical acceleration response spectra for bedrock at Christchurch.

The consequence of assuming a constant shape for bedrock acceleration spectra at Christchurch is that exceedance probabilities/return periods calculated for accelerations at one natural period (e.g. the period corresponding to peak acceleration) also apply to other accelerations scaled from this value. This simplifies analysis considerably.

Exceedance probabilities are predicted at Christchurch for various peak bedrock spectral accelerations (assumed at natural period T=0.2 seconds). Following the analysis of Berrill (1985) a probability enhancement factor $B_z=1.6$ is calculated for the Canterbury region and applied to accelerations. Probabilities for low peak spectral accelerations ($a_s \leq 0.15g$) are dominated by small to medium local earthquakes while those for high accelerations ($a_s \geq 0.45g$) are dominated by large earthquakes on the Alpine Fault.

As discussed above for intensities, the incident accelerations at bedrock will be considerably modified as they propagate upwards through the loose, cohesionless alluvium to the ground surface. Four separate effects are possible:

- Amplification due to geometric focusing by non-planar basement geology
- Amplification due to impedance mismatch between bedrock and overlying soil
- Constructive and destructive interference between incident and reflected waves in layered soils
- Attenuation due to dissipation in soft soils, particularly of high frequency components

The first effect above is expected to be negligible compared to the other three beneath Christchurch, and is not considered in this study.

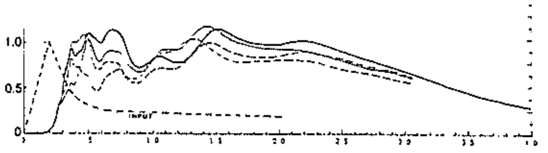
A three dimensional model of the geology beneath the city was constructed from a database of over 20,000 borelogs, to depths up to 500m, compiled by Soils & Foundations Limited (Elder et al, 1991). Results of seismic profiling reported by Kirkaldie & Thomas (1963) and by Dibble et al (1980) were also used to estimate soil types and the bedrock interface at greater depths. The method of analysis is described by Elder et al (1991a).

Response spectra at the ground surface in Christchurch were calculated at each point on a 500m grid across the city.

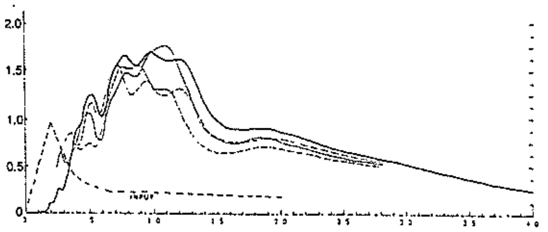
The effects of the deep alluvium are generally threefold:

- Removal of short period spectral accelerations by hysteretic damping
- Marked increase in peak spectral accelerations across most of the city
- Shift in spectral shape towards the longer period end of the spectrum, with peak accelerations occurring at natural periods 0.5 - 1.5 seconds

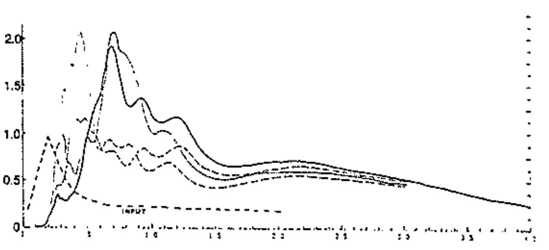
The spectral shape at any location depends strongly on the soil profile at that location, but modifications to acceleration response spectra are considerably greater than those expected if the current New Zealand Loadings Code were used to predict these effects. Although the deep soil effects influence the overall spectral magnitudes and shapes, three general shapes can be differentiated and are dependent most strongly on soil types within 20m of the ground surface. Examples of these acceleration response spectra are shown in Figure 4. Almost all calculated spectra can be placed into one of these three groups.



(a) Spectral Shape A - Fine Grained Soils, 10 - 20 m Depth



(b) Spectral Shape B - Fine Grained Soils, 5 - 10 m Depth
- Coarse Grained Soils, 10 - 20 m Depth



(c) Spectral Shape C - Coarse Grained Soils, 5 - 20 m Depth

Figure 4. Acceleration Response Spectra at the Ground Surface in Christchurch

Using the soil profile criteria defining the three spectral shape groups in Figure 4, and the 3-dimensional geological model defined at each node on the 500m grid, the city is subdivided into microzones for seismic response prediction. The peak spectral acceleration at the ground surface increases above the bedrock acceleration on average by about 20%, but by up to 100% in many parts of the city.

Return periods predicted for different spectral accelerations at Christchurch are shown in Figure 5. At all return periods, spectral accelerations predicted for Christchurch in this detailed, site specific study considerably exceed those previously expected. For a return period 150 years, peak spectral accelerations are likely to be 0.55g - 0.9g. The national study by Matuschka et al (1985) indicates a peak spectral acceleration about 0.45g at this return period. The amplification predicted is more pronounced for smaller earthquakes at shorter return periods, but slightly less marked for larger events.

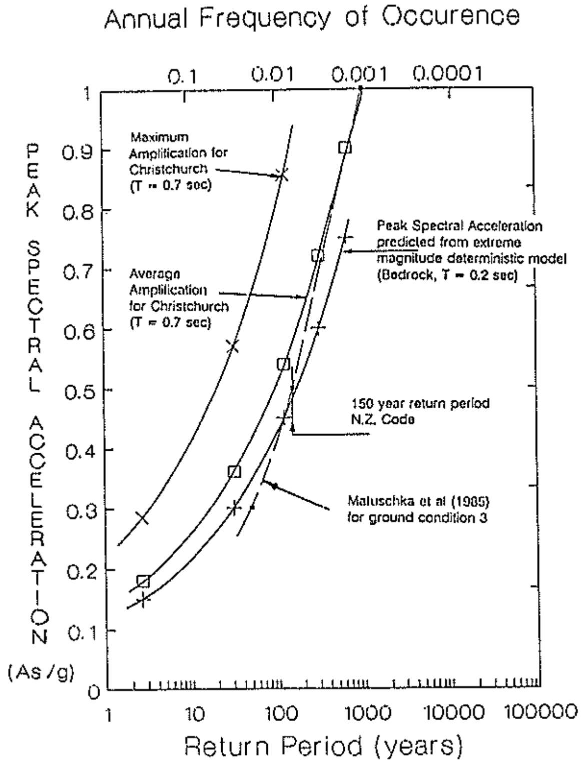


Figure 5. Return Periods for Amplified Peak Spectral Accelerations at Christchurch.

6. CONCLUSIONS

Analysis of data from historical earthquakes suggests that Christchurch regularly experiences earthquake effects considerably more severe than is generally thought. This is due to higher levels of active seismicity near the city, and the amplification effects of deep, loose, cohesionless alluvium up to 1 km deep beneath the city.

Detailed evaluation of historical and instrumental seismicity together with tectonic studies of active faulting zones, around Christchurch and in central/north Canterbury, provides evidence that the recent quiescence of major seismic activity within 150 km of Christchurch is an anomaly. The city can expect to generally experience earthquake effects in the medium strength range about as frequently as Wellington. This regularity of seismic shaking was observed in the first 70 years of the city's history; it is only since 1930 that Christchurch has not experienced significant effects from a large earthquake.

A 3-dimensional geological profile has been constructed for the alluvium beneath the city, based on a compilation of over 20,000 soil records and results of seismic surveys. Analysis of likely earthquake effect amplification has been carried out on a 500m grid across the city.

Intensities in Christchurch are likely to be magnified by up to 2 MM units above those intensities which would be felt at comparable epicentral distances on bedrock, and by at least one MM unit above intensities felt on "average ground".

Spectral response accelerations in Christchurch may be up to twice those for equivalent sites on bedrock. The natural period at peak acceleration response is likely to be 0.5 - 1.5 seconds. This shifts acceleration response spectra for the city well outside those spectra derived in the current New Zealand Loadings Code.

Probabilistic assessment for both intensities and spectral accelerations predicts that the hazard from events with return periods less than 150 - 300 years is considerably greater than suggested by previous studies. At longer return periods the hazard is also increased, but less markedly.

The consequences of these findings for specific hazards in Christchurch are discussed in companion papers. Yetton et al (1992) consider the potential for seismically triggered landslides in and around Christchurch. McCahon et al (1992) analyse liquefaction potential for the city using the same 500m grid employed in this study.

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