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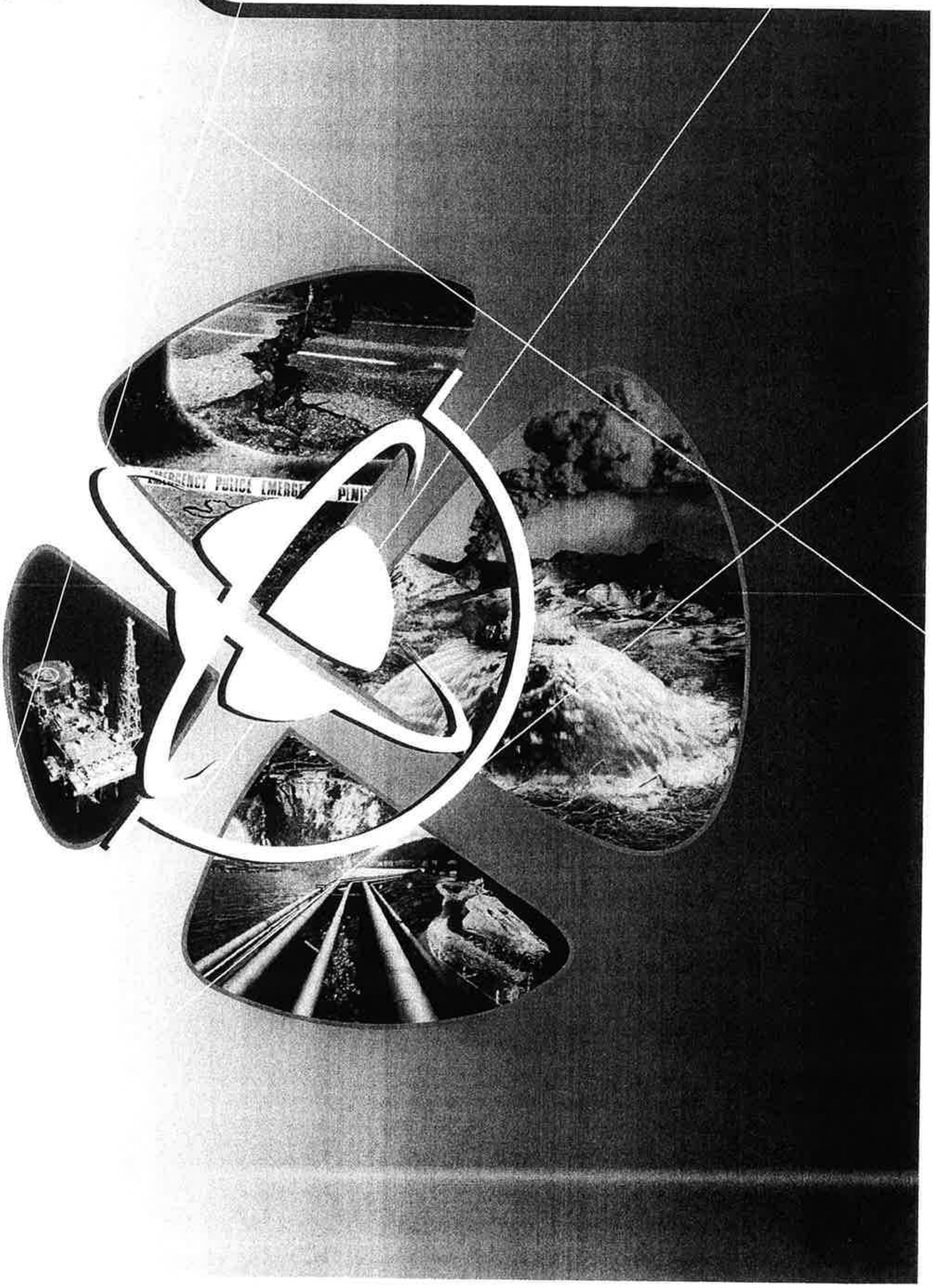
Estimated damage and casualties from earthquakes affecting Christchurch

Confidential

by Jim Cousins

Client Report
2005/057
May 2005



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Prepared for

Christchurch City Council

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Institute of Geological & Nuclear Sciences client report 2005/57
Project Number: 430W1160

The data presented in this Report are
available to GNS for other use from
May 2005

COMMERCIAL – IN – CONFIDENCE

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Study Validation Period
May 2010

The findings contained within this report remain valid until the above date, after which time the study should be re-validated to reflect the current rapid advances in the science that underpins the study.

CONTENTS

EXECUTIVE SUMMARY

Earthquakes can occur anywhere in New Zealand, but the rate of occurrence varies greatly throughout the country with the highest activity being along an axis extending from the Alpine fault, on the western side of the South Island, through Wellington to Hawke's Bay and the East Cape Peninsula. Christchurch lies in an intermediate seismicity zone some distance from the zone of high activity. However known earthquake sources, in particular the Ashley, Springbank and Pegasus fault zones, are present within the region and are large enough and close enough to cause significant damage throughout the city.

Earthquake risks to the buildings and people of Christchurch City Council have been estimated by subjecting the city to a very long, one million year, synthetic catalogue of earthquakes that represents the seismicity of New Zealand. For each of the approximately five million model earthquakes the ground shaking throughout Christchurch has been estimated, taking into account local ground conditions. Damage to buildings, collapse, and casualty levels were then estimated using models based on historical data from New Zealand and abroad. Casualty estimates were made twice for each earthquake, once for daytime conditions and once for night-time.

The buildings of Christchurch were divided into two broad classes, residential and workplace, with respective estimated replacement values of $27 billion and $12 billion (in $2005). From census data the population was estimated to be 318,000. For modelling the buildings were further subdivided into four fragility classes, viz. unreinforced masonry, timber framed, pre-1980 reinforced concrete, and 1980 onwards reinforced concrete.

Estimated losses and casualties (dead plus seriously and moderately injured) are:

Return Period (years)	Loss ($millions)	Casualties
100	190	0
500	750	6
1000	1200	16

1.0 INTRODUCTION

The Christchurch City Council has requested a study of earthquake risks to the people and property of Christchurch. The requirement was for assessment of losses and casualties due directly to earthquake damage. Indirect losses, such as business interruption, were not part of the investigation.

Although Christchurch regularly experiences earthquake shaking there appear to have been no earthquake casualties in the area since Europeans first settled in the early 1800's [15]. Nevertheless casualties and significant damage are probable in the future because there are several known active faults within 20 to 50 km of the city, and damaging earthquakes could occur even closer.

Assessing earthquake risk to a given portfolio of assets involves a number of aspects. The first is knowledge of the earthquakes that are likely to affect the assets, i.e. where they are located, how often they are likely to occur, and how large they are likely to be. The second is knowledge of the likely severity of ground motion that will occur in the earthquakes and to which the asset portfolio will be subjected. The third is knowledge of the types of buildings and their vulnerabilities to strong shaking of any given intensity, i.e. the likely degree of damage and the likelihood of collapse. The fourth is the value of the buildings, and the numbers of people in them at various times of the day. These four items can be combined to produce a risk estimate for casualties and material damage to the asset portfolio.

Studies of earthquakes and their sources in New Zealand have yielded a model of how often and where they are likely to occur, and how large they are likely to be. Using the model we have constructed a synthetic catalogue of earthquakes that statistically matches the long-term seismicity of New Zealand and which, when combined with a model of the likely strength of shaking, gives estimates of the level of shaking hazard in Christchurch together with the annual probabilities of occurrence.

Studies of the damage sustained by buildings in New Zealand and California during large earthquakes have yielded models of the likely performance of various classes of buildings, and how that performance varies with the strength of shaking. It is possible, therefore, to predict the performance in future earthquakes, albeit in an average sense because buildings vary significantly in their age, strength, shape and design. Such data have been used to provide fragility and damage estimates for the various types of buildings that are found in Christchurch. Models based on worldwide data on collapse and casualty rates have then been used to estimate the numbers of casualties for both daytime and night-time conditions.

The report has been reviewed by Warwick Smith and Andrew King of GNS.

2.0 MODELLING EARTHQUAKE HAZARDS

2.1 Overview

Seismicity in New Zealand varies regionally from moderate to very high on a world scale. Wellington, the capital, lies in one of the most active of New Zealand's seismic regions and Auckland, New Zealand's largest city, in one of the least active. Activity in the Christchurch and Dunedin areas is intermediate between that of Wellington and Auckland. These differences are illustrated by Figure 2.1, which shows the locations of the major shallow earthquakes that have occurred in the New Zealand area since 1840.

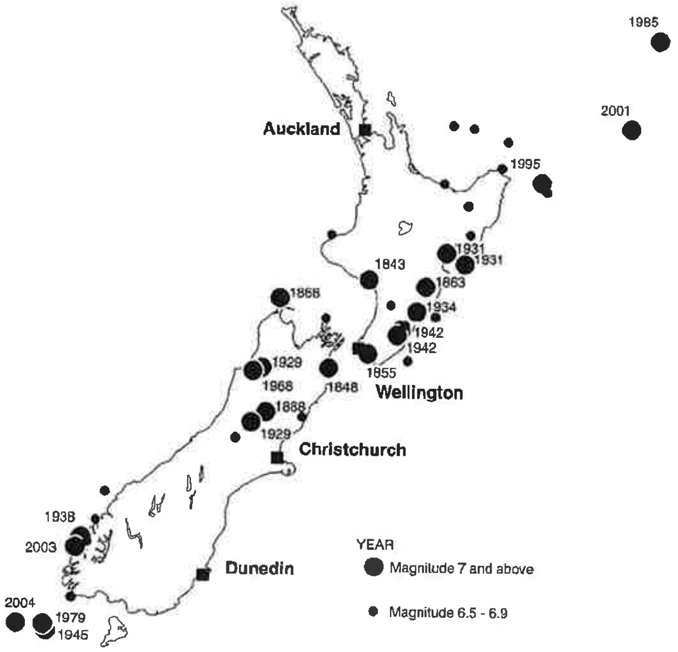

Figure 2.1 Occurrence of large shallow earthquakes in New Zealand since 1840.

The above differences in seismicity are explained by the tectonic settings of the four cities. New Zealand straddles the boundary of the Australian and Pacific plates (Figure 2.2) where relative plate motion is obliquely convergent across the plate boundary. The relative plate motion is expressed in New Zealand by the presence of many active faults, a high rate of "small-to-moderate" earthquakes (M<7), the occurrence of many "large" earthquakes (M7-7.9) and one "great" earthquake (M>8) since 1840.

A southeast-dipping subduction zone lies at the far south-western end of the country ("Fiordland subduction zone" in Figure 2.2). It is linked to a major northwest-dipping subduction zone in the eastern North Island ("Hikurangi subduction zone") by a 1000 km long zone of right-lateral oblique slip faults ("Axial tectonic belt"). Essentially all of the relative plate motion is accommodated by the faults of the axial tectonic belt in the area between the two subduction zones.

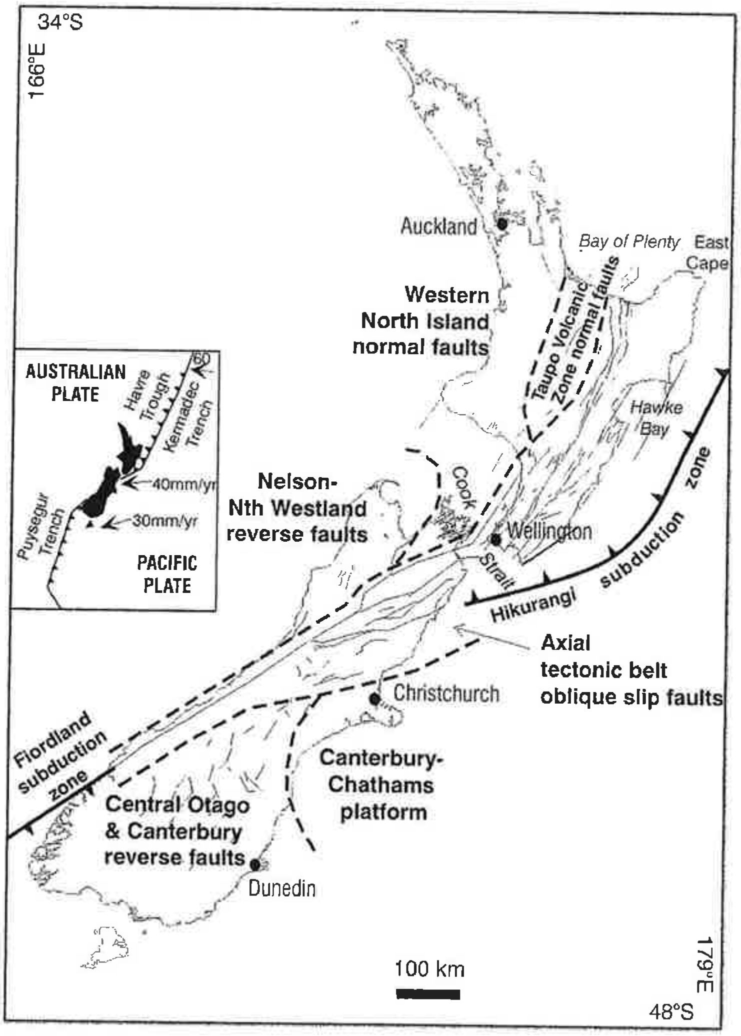

Figure 2.2 Tectonic setting of New Zealand

Some of the highest rates of seismicity in the country occur within the dipping slabs of the subduction zones. Frequent moderate earthquakes also occur above both of the subduction zones. However, only one large earthquake and no great earthquakes are known to have been produced by the Hikurangi subduction zone since 1840, and so little is known about the earthquake potential of this feature.

The axial tectonic belt is a zone that is characterised by right-lateral strike-slip motion and compression. Many moderate or larger earthquakes have occurred within the axial tectonic belt in historical time, including New Zealand's two largest historical earthquakes (the M_w8.2, 1855 Wairarapa earthquake, and M_w7.8 1931 Hawke's Bay earthquake). The axial tectonic belt also includes the Alpine Fault, which accommodates virtually all of the relative plate motion in the central South Island. It has not produced any large or great earthquakes since

1840, although geologic data provide evidence for the occurrence of great earthquakes on it with return intervals of about 300 years.

2.2 Major urban centres

Auckland is situated about 300 km from the Hikurangi subduction zone. Faults close to Auckland are generally either inactive or have low levels of activity. The nearest known moderately active faults are about 30-60 km from central Auckland. They are thought to be capable of generating earthquakes of magnitude about 6.5 and are expected to rupture on average every 5,000-10,000+ years.

Wellington is located in the boundary zone between the Pacific and Australian plates. It lies above the Hikurangi subduction zone where the Pacific plate is sinking beneath the Australian plate, 25 km or so beneath Wellington City. Crustal strain caused by the inter-plate motions is accommodated by several active faults in the Wellington region. One of the most active is the Wellington Fault which runs through the centre of the urban area, ruptures on average once in about 600 years, and is capable of producing earthquakes of about magnitude 7.5.

Christchurch is located about 130 km from the Alpine fault, which is the centre of major crustal strain in that part of the South Island. The nearest known active faults are the Ashley, Springbank and Pegasus Bay fault zones about 25 km to the west and north of the city. All are thought capable of generating earthquakes of about magnitude 7, rupture on average every 2000-10,000 years, and together contribute most of the seismic hazard in Christchurch.

Dunedin city is 250 km from the Alpine fault, but an active fault, the Akatore fault, may extend to within a few km of the city's centre. It is thought to be capable of generating earthquakes of about magnitude 7 once every 3,000 years or so.

2.3 Definitions of intensities and intensity zones

Seismic risk modelling undertaken by GNS usually relies on the Modified Mercalli (MM) Intensity scale as a measure of the strength of seismic shaking. Maps of shaking intensity (e.g. Figure 2.3) have been produced for most large historical earthquakes in New Zealand. They contain spot estimates of intensity derived from reports returned by people in the area, and contours, called isoseismals, which delineate zones of various strengths of shaking. An "intensity zone" is the area between two adjacent isoseismals and is defined such that the intensity 5 zone, for example, is the area between the MMV and MMVI isoseismals. Ideally all of the spot intensities within a given intensity zone would have the same value and there would be no instances of that value outside of the zone, but this almost never occurs in practice because of the natural variability of earthquake phenomena. The drawing of the isoseismals thus relies heavily on judgement.

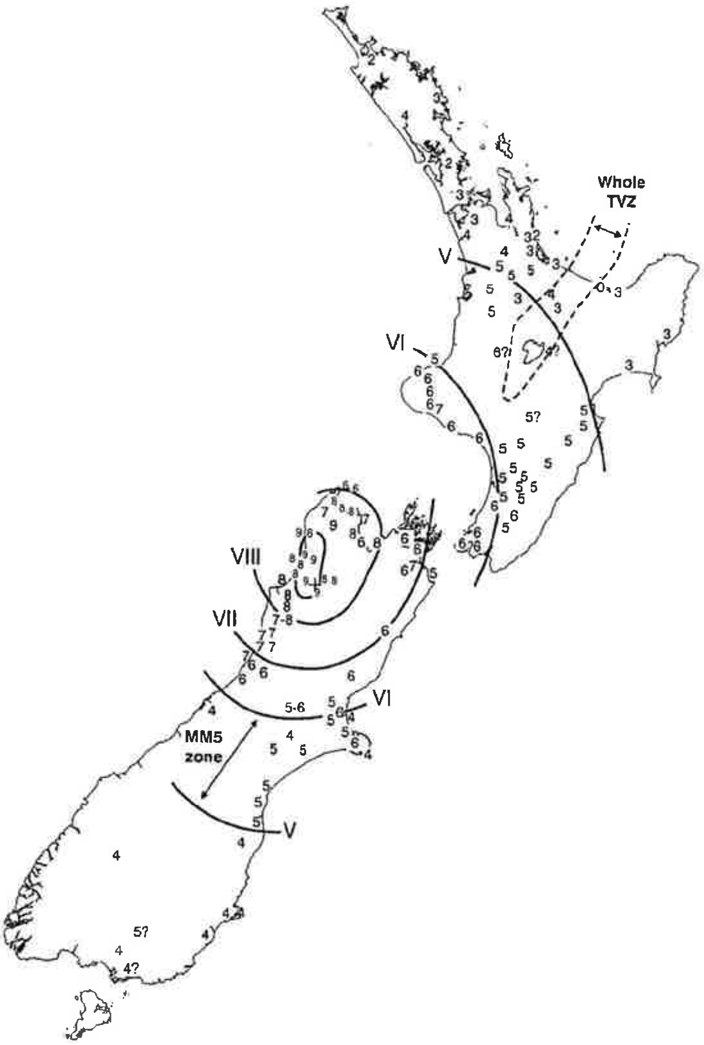

Figure 2.3 Map showing a typical example of Modified Mercalli intensity isoseismals, using data from the magnitude 7.7 Murchison (Buller) earthquake of 1929 [8]. An intensity zone is the area between two adjacent isoseismals, e.g. the MM5 zone is the area between the MMV and MMVI isoseismals.

Because of the way in which the MM intensity scale is defined, the spot intensity values are constrained to be integer numbers. In reality the attenuation of shaking is not an integral process, and for attenuation modelling the intensities are decimalised. The MMV isoseismal is defined as being intensity 5.0 in the attenuation model, MMVI as 6.0, and so on. The decimal intensity at, for example, the centre of the MM5 zone is 5.5. The attenuation models, therefore, predict the radii of decimal-number isoseismals.

For practical reasons, studies of damage costs [e.g. 9] are usually based on whole intensity zones, and, unless there are good reasons to do otherwise, the resultant damage ratio values should be positioned at the centres of the intensity zones when they are plotted as functions of intensity. Importantly, because the mean damage ratios are derived from observations over relatively large areas they, implicitly, take into account the variability of intensity that occurs over such areas.

2.4 Earthquake hazard assessment

2.4.1 Seismicity model

Stirling *et al.* [29] have established a database of the locations and characteristics of 305 known active faults for New Zealand. For each of the faults a characteristic magnitude, mechanism and mean recurrence interval have been estimated. In many cases the parameters have been estimated by detailed paleoseismic studies involving excavation of trenches across the faults. For others the parameters have been estimated by other means, including comparisons with nearby faults and general understanding of the fault behaviour in various tectonic regimes. Although the completeness level of the database is unknown, the 305 faults are considered to be the sources of most large earthquakes in New Zealand.

Known active faults comprise only part of the earthquake hazard. Many significant active faults in New Zealand do not extend to the ground surface and hence we cannot be sure that all have been identified (in fact we are sure of the converse!). A good illustration of this is the Hawke's Bay earthquake of 1931. Even though it was a large earthquake, magnitude 7.8, and caused extensive ground deformation, the primary rupture did not propagate to the surface. Hence that highly significant earthquake source was not recognised prior to 1931.

To account for earthquakes on the presently "unknown" (especially buried) faults, seismicity models for New Zealand include what is called "distributed seismicity". The "distributed seismicity" model consists of magnitude and occurrence rate parameters defined at a grid of some 40,000 points that cover the country and extend to 90km depth. Thus the seismicity is represented as a smoothly varying background occurrence rate, very low in the north and high in the main axial belt from East Cape to Fiordland. In the vicinity of Christchurch the distributed seismicity model allows for earthquakes of up to magnitude 7.0.

Using the two parts of the seismicity model, we have generated a synthetic catalogue that represents the earthquakes likely to occur throughout New Zealand over a one million year period. The catalogue provides a powerful means of estimating earthquake risk: the procedure is to estimate the likely effects of every earthquake in it, then to estimate how much damage ensues, and how often.

2.4.2 Attenuation models

In order to estimate the expected severity of ground motion (intensity) at any given place, due to an earthquake elsewhere, we need a suitable attenuation model. We use the model of Dowrick & Rhoades (1999) [14], which describes the attenuation of MM intensity for New

Zealand earthquakes. It takes into account not only the magnitude of the earthquake and its location, but also its focal depth, mechanism and the orientation of the fault source.

An important point about the Dowrick & Rhoades model is that it predicts shaking intensities for average ground. Actual intensities on non-average ground, i.e. soft soil or rock, can be higher or lower than the average-ground case as a result of microzonation phenomena.

2.4.3 Uncertainties in ground motion

Two sources of ground motion uncertainty are addressed. The first is that the characteristic magnitudes are not known precisely. Successive earthquakes on any given fault may rupture different lengths of the fault, hence are unlikely to be of *exactly* the same magnitude. We take this into account by allowing the characteristic magnitudes to vary over a small range as the synthetic catalogue is produced. So in the synthetic catalogue, successive earthquakes on the same fault have a range of magnitudes, which are clustered around the nominal characteristic value. Secondly, even if the magnitudes were known precisely, the ground motion could not be predicted with absolute confidence, because the Dowrick & Rhoades formula is obtained by fitting observed data, and this fit is not precise. The implication of this is that successive earthquakes on a fault will not generate identical ground motion at any particular location, even if the magnitudes are equal. There will be a distribution of intensities representing the uncertainty in the attenuation formula. This second source of uncertainty is accommodated by allowing a small variation in the ground motion as calculated for locations of interest.

2.5 Microzonation phenomena

Microzonation is the term used to describe how local ground effects modify the seismic shaking that is experienced at a specific site. Various phenomena can be involved. Of most relevance to seismic risk studies are amplification of shaking by soft soils, liquefaction, landsliding, and topographic enhancement of shaking.

2.5.1 Amplification

Amplification of seismic shaking by soft soil is a controversial subject. While certain types of soil can amplify low levels of input rock motion while the soil remains elastic, once the soil is excited beyond its elastic range (MM8 and above) soft soils can isolate surface structures from the strong shaking.

Amplification is most obvious when the input rock motions are relatively weak and caused by large, distant earthquakes. An extreme example occurred in Mexico City in 1985. The earthquake causing the damage was a magnitude 8.1 event located near the Pacific coast of Mexico about 400 km away from the city. On firm ground adjacent to the city the shaking intensity was quite weak, about MM5, but on certain soft soils within the city shaking was strong enough to seriously damage many modern high-rise buildings and kill more than 10,000 people. One reason for this was a double resonance effect. Areas of soft soils that had resonant periods of about 2 seconds were preferentially set in motion by the incoming seismic waves, and buildings that had the same resonant frequency, typically being those 8-16 stories high, swayed particularly strongly. Many collapsed. Nearby buildings of weak stone construction were undamaged because their resonant periods did not match the resonant period of the soft soils [22].

A second example occurred in San Francisco during the 1989 Loma Prieta earthquake. Downtown San Francisco was nearly 100 km from the epicentre of the magnitude 7.1 earthquake. On firm soils and rocky areas of the city the prevailing intensity was MM6, increasing to MM7 on some adjacent softer soils and to MM9 in some small pockets of very soft soils [1]. However liquefaction effects also contributed to the damage associated with the very soft soils.

In both Mexico City and San Francisco the soft soils have repeatedly shown the same amplification effects, e.g. in Mexico City in 1957, 1979 and 1985, and in San Francisco in 1906 [4] and 1989.

What happens in these locations when the input motions are very strong is not at all clear, however. In 1931 when Napier was subjected to MM10 shaking from a nearby, magnitude 7.8 earthquake, for example, shaking damage increased with the strength of the subsoil. Houses on ground classified as rock were, on average, more badly damaged by ground shaking than houses on ground classified as firm soils and gravels, which in turn were more badly damaged than most houses on ground classified as soft soil [17]. (Note that houses on soft soil that suffered lateral spreading, about 10% of all houses on soft soil, were the most badly damaged of all and are excluded from the above discussion.)

A second example of the "isolation" effect of soft soil was noted in Los Angeles after the magnitude 6.4 Northridge earthquake of 1994. Over a considerable area there was an anti-correlation between house damage and pipe damage, i.e. where houses were highly damaged underground pipes were not and vice versa. It seemed that where there were large strains in the soil (but excluding regions of differential settlement and lateral spreading) the soil absorbed enough seismic energy to significantly protect the houses on it, while extensively damaging the buried pipe networks [33,34].

Amplification of weak seismic shaking by soft soils has been seen many times in recordings made by arrays of seismological instruments in Wellington, Lower Hutt and Porirua [e.g 27,32]. Conversely, data from around the world shows that peak ground accelerations and short-period vibrations appear to be attenuated on soft soils for accelerations above about 0.4g, i.e. for intensities greater than about MM8 to MM9.

To summarise, amplification of seismic shaking intensity in soft soils is expected to occur:

- for all periods at low levels of excitation (< MM8) and
- for long periods (> 0.6 seconds) only at strong levels of excitation (> MM8).

Shaking intensity on average ground lies between that of rock and soft soil. This means that relative to the average-ground shaking as predicted by the Dowrick & Rhoades attenuation model, shaking on soft soil is often stronger and shaking on rock is often weaker.

2.5.2 Topographic enhancement of shaking

Amplification of shaking can also occur at the crests of ridges and hills, the effect being somewhat analogous to the increase of height in water waves approaching the edge of a beach. Increased damage to structures can occur as a result. We have neither maps of the relative level of risk from topographic amplification, nor firm data that would enable us to quantify the additional damage that would result from topographic enhancement of shaking. For Christchurch, any topographic enhancement is expected to be restricted to the crests of ridges in the Port Hill area.

2.5.3 Liquefaction

Liquefaction is the term used to describe the loss of bearing strength experienced when uniformly graded, saturated, sand is subjected to dynamic shaking. Its effects can range from harmless sand boils to serious ground damage such as subsidence, lateral spreading and loss of bearing strength. At intensities of MM6 to MM7 the effects of liquefaction are nearly always small and rarely cause significant damage to buildings and equipment. At higher intensities, MM8 and above, ground damage (settlement, spreading or displacement) often occurs and can result in substantial damage to buildings. However, it seldom actually does so in New Zealand (in natural ground) because not many urban areas of New Zealand have extensive areas of soils with high liquefaction potential.

Not all assets are equally at risk from liquefaction, and experience shows that well-founded buildings can withstand the effects of liquefaction. During the Kobe (Japan) earthquake of 1995 for example high-rise buildings on piles were almost completely undamaged by the severe liquefaction that affected several tens of square kilometres of ground and paralysed one of the world's largest container ports. Of course the services connections to the buildings were severed when the ground around the buildings settled by about 0.5m, but the buildings themselves suffered only shaking damage [23]. Some of the smaller buildings showed various amounts of tilting and settlement, but most did not.

Structures that are either buried in the ground, or are on the surface but not mechanically stronger than the ground beneath them, are much more susceptible to liquefaction-related damage than are buildings [25]. Included in this category are buried pipelines, buried tanks, stopbanks, earthen dams and other earthworks like drains.

Potentially liquefiable soil types occur in many parts of Christchurch, generally in discontinuous lenses or layers extending to depths of several metres and capped by about 2m of materials that are unlikely to liquefy. However interpretations of the liquefaction hazard that might result from such a soil structure vary greatly [e.g. 3,5 ,21].

We are not aware of any historical reports of liquefaction in Christchurch City, but this is not surprising given that the highest shaking intensity reported from Christchurch in historical times is MM7.

In allowing for liquefaction in Christchurch we assume that ninety percent of the flat land of Christchurch is "soft" and susceptible to liquefaction, but that in any particular earthquake the proportion of flat-land buildings likely to be adversely affected by lateral spreading or settlement is small, say five percent. In Napier in 1931, ten percent of the buildings on soft ground were adversely affected by lateral spreading or settlement [17]. However the shaking intensity in Napier was MM10, which much stronger shaking than is ever likely to be experienced in Christchurch.

2.5.4 Earthquake-induced landslides

Strong shaking in earthquakes is a major cause of landslides in New Zealand. Factors that are important in determining the stability of sloping ground include the slope angle, the slope height, slope modification, the underlying geology, existing landslides, and groundwater content [20]. Properties below and above areas of high landslide susceptibility also are at risk should landsliding occur, from burial and undermining respectively. Slope instability in the Christchurch urban area is confined to the Port Hills area [3,5].

2.5.5 Microzonation loss allowances

We expect neither liquefaction nor earthquake-induced landsliding to have major impact on buildings in Christchurch, primarily because of the relatively low levels of the intensities anticipated in future earthquakes (≤ MM8). For intensities below MM8, landslide effects are likely restricted to rock falls on steeper (>30°) slopes such as coastal cliffs, road cuts and excavations, and small areas of minor shallow sliding. There may also be a few instances of non-damaging liquefaction (small water and sand ejections) in alluvium. At MM8 (zone) shaking there may be significant areas of shallow sliding of alluvium and small to moderate failures of cuts, road-edge fills and cliffs. Evidence of liquefaction is likely to be common, with localised lateral spreading and settlements along the banks of rivers, lakes etc.

A brief survey of historical data for Christchurch, Appendix 1, suggests that amplification might be significant for Christchurch. The "amplification" is relative to the levels of shaking predicted by the New Zealand attenuation model, and could include either or both of soft-soil amplification and topographic enhancement. Although there is only a limited amount of historical data, and there are no instances of the important intensities of MM8 and MM9, the results of Appendix 1 do seem to indicate a tendency for the higher historical intensities from Christchurch to be underestimated by the New Zealand attenuation model.

We have no firm data for guidance as to the increased (on soft soils) or decreased (on rock) intensities of shaking that might result from the various microzonation phenomena. As a matter of judgement we assume the following increments relative to the average-ground intensities as predicted by the Dowrick & Rhoades model. Firstly, for soft soils, up to MM7 there is an increase in intensity of 0.5 of an MM intensity step as a result of amplification. For intensities of MM9.0 and above there is an increase of 0.05 as a result of lateral spread and settlement. Between MM7.0 and 9.0 there is a steady change in the increment as shown in Figure 2.4. For rock, up to MM7 there is an effective decrease in intensity of 0.5 of an MM intensity unit. From MM7.0 to MM9.0 this de-amplification becomes steadily smaller, in part due to topographic enhancement and landsliding. For MM9 and higher it is equivalent to 0.05 of an MM intensity step.

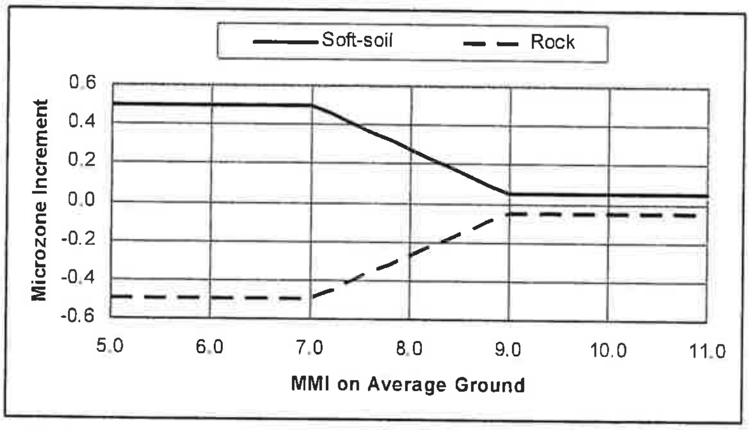

Figure 2.4 Changes in shaking intensity, relative to the "average-ground" intensity modelled by the Dowrick & Rhoades attenuation model, due to microzonation.

2.6 Tectonic movements

Earthquakes are sometimes accompanied by tectonic movements, which are the subsidence or uplift of large blocks of land. Areas of hundreds to thousands of square kilometres can be affected, and changes in elevation of several metres have been observed. During the 1987 Edgecumbe earthquake, for example, there was 1 to 2m subsidence of about 30% of the Rangitaiki Plain. The cost of countering the effects of the subsidence, i.e. increasing the heights of stopbanks, additional pumping, and re-grading drains, was approximately equal to the cost of repairing shaking damage to the flood protection structures.

We do not expect Christchurch to be affected by tectonic movements in future earthquakes, largely because of the distance of known active faults from the city.

2.7 Seismic hazard in Christchurch

Early studies of the seismic hazards affecting Christchurch [e.g. 2,5,19] indicated a relatively high seismic hazard level, only marginally lower than that of Wellington. More recent studies, however, indicate a lower level of hazard which is more in keeping with the location and activity of all earthquake sources (i.e. both close-in distributed seismicity sources and known fault sources) [16,24,30,31]. The recent results are also more consistent with the historical record [11] than the earlier ones, and have been used as the basis of our study.

During its 160-year recorded history Christchurch has not experienced MM8 shaking, and only occasionally have spot intensities of MM7 been observed. The highest isoseismal (zone) intensity experienced has been one occurrence of MM7 [31]. That was due to an earthquake of magnitude about 5 and which was probably centred within the present city limits.

Table 2.1 gives an overview of the shaking hazard in Christchurch as indicated by the current GNS seismicity model for New Zealand. Two return periods are given for each intensity level, one for average ground (as assumed by the New Zealand model) and one for soft ground typical of the central business district of Christchurch. The differences are due to the behaviour of soft soils during earthquake shaking, leading to amplification of shaking or liquefaction depending on the strength of the shaking.

Table 2.1 Return periods for shaking intensity in Christchurch, with and without taking into account the influence of microzonation phenomena such as soft-soil amplification and liquefaction.

MM Intensity	Return Period (years) (without microzonation)	Return Period (years) (with microzonation)
≥ 6.0	24	10
≥ 7.0	140	50
≥ 8.0	1800	600
≥ 9.0	74,000	20,000

3.0 THE ASSETS AT RISK

3.1 Buildings

The buildings model consisted of estimated replacement values and floor areas for all buildings in Christchurch, aggregated into groupings of two to four suburbs in size. In all there were 27 such data aggregates, each of which was regarded as being at a single geographic location. The spacing between the point locations was about 3km.

The base data for the buildings model were rating values and floor areas obtained from Quotable Value New Zealand. Because the data were provided in aggregated form it was not practicable to incorporate information related to age, structural type, and height. Replacement values, required for the loss modelling, were estimated from the base data by using the supplied data to generate "corrected" floor areas, which then were multiplied by estimated construction costs. The original data were subdivided into nine usage categories, for example commercial and industrial, but were condensed to just "workplace" and "residential" for the Christchurch model.

The total estimated replacement values and floor areas were:

Residential:	\$27 billion	21 million square m
Workplace:	\$12 billion	11 million square m

The aggregated buildings model is suitable for modelling losses due to large-scale hazards where the spatial variation in the hazard is commensurate with the spacing between the data points. It is well suited, for example, to estimating losses from moderate to large earthquakes, especially those affecting urban areas, because the scale of variation in the shaking intensity ranges from kilometres for the near-source isoseismals to tens of kilometres for the distant ones. The effect of the aggregation has been investigated by comparison of loss estimates based on the aggregated model with those from a highly detailed property-by-property model for Wellington City [6,7]. Allowing only the degree of aggregation to vary between the two models, Wellington City was subjected to five magnitude 7.3 earthquakes located at various points along the Wellington Fault. In all cases the two models gave loss estimates that were within 4% of each other.

The fragility of a building depends on many factors, most particularly the type of construction and the date of construction. Four major classes were used for the present study with assumed proportions as in Table 3.1. Unreinforced masonry construction (URM – typically brick buildings constructed prior to 1940) is particularly important because it is highly fragile and contributes disproportionately to losses and casualties. Timber-framed buildings on the other hand are highly resistant to collapse, though they do contribute significantly to repair costs.

Age has a relatively minor impact on the fragility of timber-framed buildings, but is highly significant for concrete buildings. Although construction codes have been improved several times since the first was introduced to New Zealand in 1935, the 1980 era represents perhaps the greatest single step. For the purposes of the present study the term "reinforced concrete" included all types of concrete construction (shear-wall, moment-resisting frame and tilt-up) and also steel-framed workplace construction. Given the lack of detailed age and type data for Christchurch, the proportions of Table 3.1 were based on detailed information for Wellington City, with the only major difference being in the proportions of URM which for Wellington were 1% and 2% respectively of that city's residential and workplace construction.

Table 3.1. Building types and proportions adopted for Christchurch.

Use Classification	Construction Type	Fraction of inventory
Residential	URM (unreinforced masonry)	0.02
	Timber frame	0.90
	Pre-1980 reinforced concrete	0.04
	1980 onwards reinforced concrete	0.04
Workplace	URM (unreinforced masonry)	0.05
	Timber frame	0.15
	Pre-1980 reinforced concrete	0.40
	1980 onwards reinforced concrete	0.40

Because more detailed information was not readily available the above building-type distributions were applied to all parts of the city. Thus the only changes from one data point to another were in the relative proportions of residential and workplace accommodation, and in the allowances made for microzonation.

3.2 People

Based on census data from 2001 [28], the year 2005 population of Christchurch was estimated to be 318,000. The people were allocated to each data aggregation point in proportion to the total floor area of the buildings associated with it, for both daytime and night-time scenarios.

At any time of the day some people are indoors at their places of work, some are indoors at home, and some are outdoors. For modelling purposes "work" means "not at home" and so includes students, shoppers, hospital patients etc. The locations of people for day-time and night-time earthquakes were as given in Table 3.2 [26].

Table 3.2. Locations of people for day-time and night-time earthquakes.

Time of day	Indoors at Workplace	Indoors at Home	Outdoors
Workday (11 a.m.)	0.58	0.22	0.20
Night-time (2 a.m.)	0.04	0.95	0.01

4.0 DAMAGE

4.1 Earthquake loss calculation

The potential earthquake loss to the buildings of Christchurch is obtained from:

$$\textbf{Loss} = \Sigma\ (\mathbf{D}_{r,i}\ \mathbf{x}\ \textbf{Replacement Value}_i),$$

where $\mathbf{D}_{r,i}$ is the fragility function for asset item "i". The fragility function we use is the "Damage Ratio", which is a function of the intensity of shaking and is given by:

$$\mathbf{D}_r = \frac{\textbf{cost of material damage to property at risk}}{\textbf{replacement value of property at risk}}$$

Most of the basic mean damage ratios used in this study were derived using, as a starting point, those estimated in recent studies of New Zealand earthquakes, i.e. Edgecumbe, 1987, Hawke's Bay, 1931 and Inangahua, 1968. Domestic property damage has been studied for all three earthquakes [9,17,18], while non-domestic property damage has been studied for the Edgecumbe earthquake only [12,13].

For guidance in estimating mean damage ratios for building types not represented in the New Zealand datasets we rely on a set of subjective estimates made for Californian buildings [25]. The relative vulnerabilities of the various types of building, based on the New Zealand and Californian experiences, are listed in Table 4.1.

Table 4.1 Relative fragilities assigned to various categories of buildings.

Construction Type	Age	Height	Use	Relative Fragility
URM (unreinforced masonry)	All ages	All heights	All uses	5.4
Timber frame	All ages	All heights	Residential	1.4
			Workplace	1.2
Pre-1980 reinforced concrete	All ages	All heights	All uses	2.3
1980 onwards reinf. concrete	All ages	All heights	All uses	1.0

For modelling purposes the damage ratio is expressed as a smooth function of shaking intensity as follows:

$$\overline{D_r} = A \times 10^{\left(\frac{B}{\text{MMI} - C}\right)}$$

where A, B and C are constants. The functions used for estimating potential earthquake losses to Christchurch's buildings are shown in Figure 4.1.

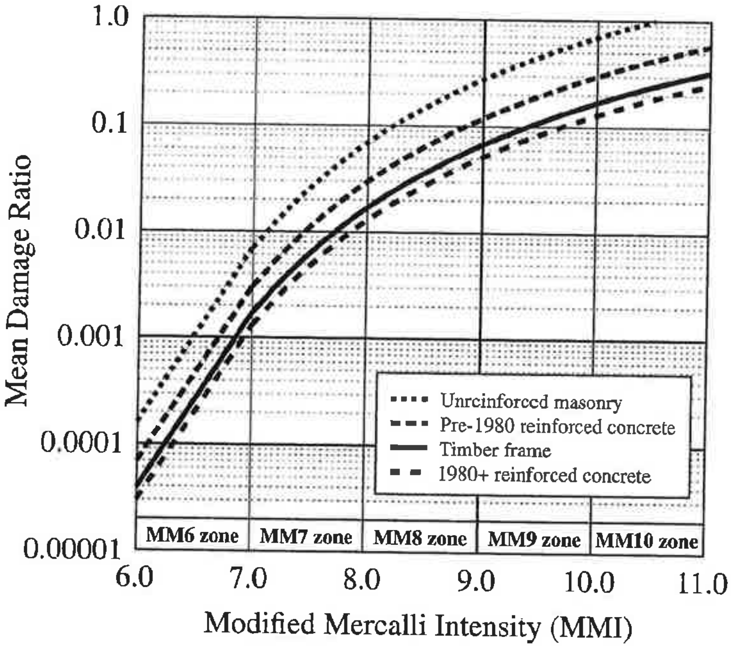

Figure 4.1 Representative mean damage ratios for buildings in Christchurch.

4.2 Estimated earthquake losses

Figure 4.2 shows the Loss Curve for the Christchurch buildings. This gives the annual probability that any given loss level will be equalled or exceeded. The same results are presented in Figure 4.3, in a different format which may prove useful: Annual Probability is represented in the form of Return Period (years), of which it is the reciprocal, and the Loss scale is linear, rather than logarithmic as in Figure 4.2. The total estimated replacement value for the assets involved is $39 billion.

Table 4.2 gives the data that are plotted as curves in Figures 4.2 and 4.3. In particular, there is a 1% annual probability of a loss of $190 million or more, and a 0.1% annual probability of a loss (rounded) of $1.2 billion or more. Alternatively, the losses having return periods for exceedance of 100, 500 and 1000 years are $190 million, $750 million and $1.2 billion.

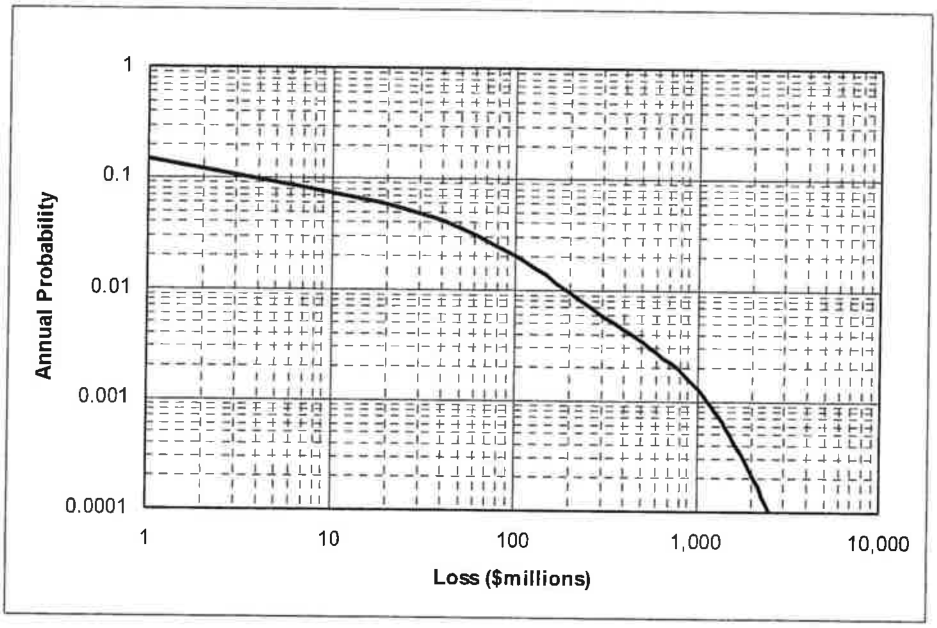

Figure 4.2 Loss curve for the Christchurch City's buildings. The annual probability shown is cumulative, i.e. it is the probability that a given level of loss will be equalled or exceeded.

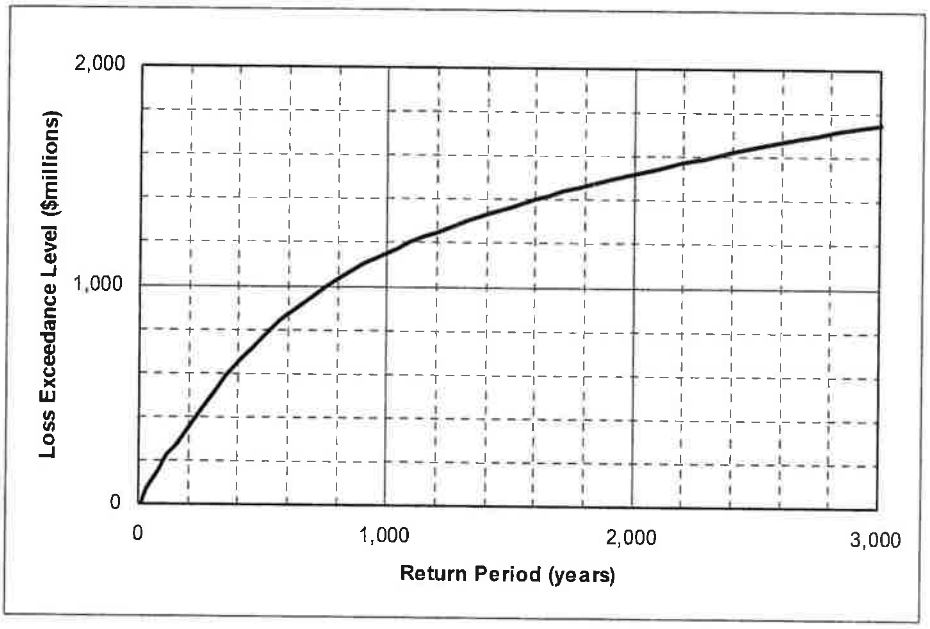

Figure 4.3 The same data as in Figure 4.2, displayed showing the loss that will be equalled or exceeded, as a function of return period.

Table 4.2 Estimated losses for various return periods for earthquake shaking affecting the buildings of Christchurch City.

Return Period (years)	Annual Probability of Exceedance	Loss ($millions)
10	0.1	4
20	0.05	30
50	0.02	100
100	0.01	190
200	0.005	350
300	0.0033	500
400	0.0025	650
500	0.0020	750
600	0.0017	850
800	0.00125	1,050
1,000	0.00100	1,150
1,200	0.00083	1,250
1,500	0.00067	1,350
2,000	0.00050	1,500
3,000	0.00033	1,750
5,000	0.00020	2,100
10,000	0.00010	2,500

5.0 CASUALTIES

5.1 Collapse model

Buildings may suffer varying degrees of collapse during earthquake shaking. From the point of view of casualties it is the loss of volume of the building that is the critical factor, with a loss of 50% being the level at which significant numbers of casualties begin to occur [26].

New Zealand data on collapse are very limited. Only one earthquake, the magnitude 7.8 Hawke's Bay earthquake of 1931, has resulted in significant numbers of collapsed buildings. Dowrick [10] has categorised the damage states of approximately 330 of Napier and Hastings' concrete and unreinforced masonry buildings. Most could be regarded as earthquake risk. About half collapsed to some degree, but only about 15% suffered volume losses of 50% or more. About 240 people were killed as a result. Of the 97 reinforced masonry or concrete buildings only 7 collapsed either partly or completely.

There has been very little New Zealand experience with the collapse, due to shaking, of buildings constructed in accordance with either current or previous New Zealand seismic design codes.

Previous studies of casualties in major earthquakes affecting the Wellington region [e.g. 26] have combined New Zealand and overseas data to produce mean collapse rates for the various classes of building present in Wellington. Similar collapse rates are used for the Christchurch model, expressed in the form

$$\overline{C_r} = A \times 10^{\left(\frac{B}{MMI - C}\right)}$$

where $\overline{C_r}$ is the mean collapse rate, MMI the shaking intensity, and A, B and C are constants (Figure 5.1).

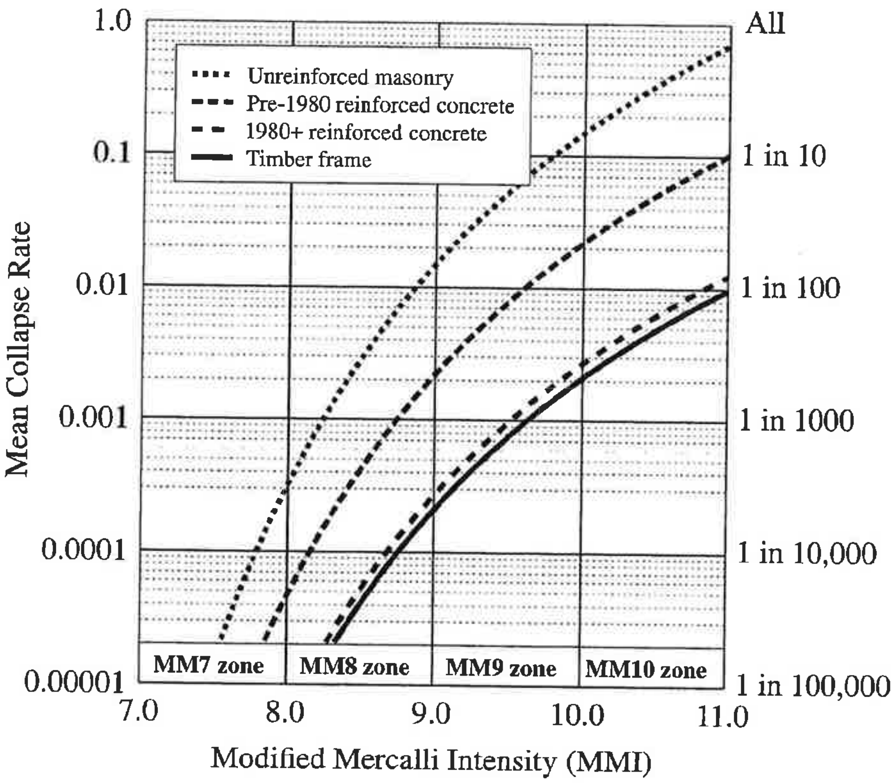

Figure 5.1. Mean collapse rates for the classes of building used in the earthquake loss model.

5.2 Casualty model

When a building collapses some of the occupants are killed, some are seriously injured, some are moderately injured, and the remainder are either lightly injured or uninjured. A serious injury is defined as one that will cause death if the person does not receive prompt medical or surgical treatment. A moderate injury is one that requires medical or surgical treatment but which is not immediately life threatening (e.g. a fractured limb), and light injuries are those that can be dealt with by first-aiders. Earthquake casualty rates for Christchurch were derived from those developed in studies of potential casualties from major earthquakes affecting central New Zealand [26] (Table 5.1).

Table 5.1 Proportions of occupants killed or injured in buildings that collapse.

Building Use	Kill Rate	Serious Injury Rate	Moderate Injury Rate
Workplace	0.20	0.04	0.12
Residential	0.01	0.005	0.10

5.3 Casualties due to fault rupture

Buildings that straddle a surface-rupturing fault are likely to be severely damaged when it ruptures. The effect is highly localised, however, and there are few places in New Zealand where it is likely to contribute significantly to damage and casualties. The most important are Wellington, Lower Hutt and Petone (all bisected by the southernmost segment of the Wellington fault), Porirua (traversed by the Ohariu fault), Whakatane (bisected by the Whakatane fault) and Masterton (bisected by the Masterton fault).

Surface fault rupture contributes relatively very little to the overall damage to buildings. In the case of the Wellington fault, for example, approximately 140 buildings are intersected by the fault [15]. Even if all were to be destroyed when the fault ruptures, the total loss of 140 buildings is minuscule compared to the shaking damage to the 100,000 or so buildings exposed to strong shaking. Hence there is no allowance for fault rupture damage in the loss model.

The situation is altogether different for casualties, which depend largely on the collapse of buildings. Because relatively very few New Zealand buildings are expected to collapse as a result of earthquake shaking, any additional collapses due to fault rupture can lead to significant increases in the numbers of casualties. Estimated casualties due directly to fault rupture range from several, for the Whakatane fault, to about 200, for the Wellington fault.

Fault rupture is unlikely to be an issue for Christchurch because there are no known surface-rupturing faults within the city boundaries.

5.4 Casualties due to miscellaneous causes

The above casualty numbers are those arising solely from the collapse of buildings. Earthquake related deaths and injuries also arise from other causes such as fire, landslide, collapsed bridges, falling glass, and panic reaction. Dowrick [26] estimated numbers of casualties from many such causes for a large earthquake affecting the Wellington region. His estimates (Table 5.2) were adopted for Christchurch.

Table 5.2 Casualties due to miscellaneous causes, expressed as proportions of the numbers due to building collapse (i.e. if there are 100 deaths due to building collapse there will be an additional 20 due to miscellaneous causes, if there are 100 serious injuries due to building collapse there will be an additional 83 due to miscellaneous causes, and so on).

Time of day	Deaths	Serious Injuries	Moderate Injuries
Workday (11 a.m.)	0.20	0.83	1.16
Night-time (2 a.m.)	0.64	2.0	1.6

5.5 Estimated casualties

Figure 5.2 shows the Loss Curve for the Christchurch casualties. This gives the annual probability that any given number will be equalled or exceeded. The same results are presented in Figure 5.3 plotted against the Return Period (years), and the Loss scale is linear, rather than logarithmic. The total estimated population for Christchurch is 318,000.

Table 5.3 gives the data that are plotted as curves in Figures 5.2 and 5.3. In particular, there is a 0.5% annual probability of one casualty (or more), and a 0.1% annual probability of sixteen. Alternatively, the numbers having return periods for exceedance of 100, 500 and 1000 years are zero, six and sixteen.

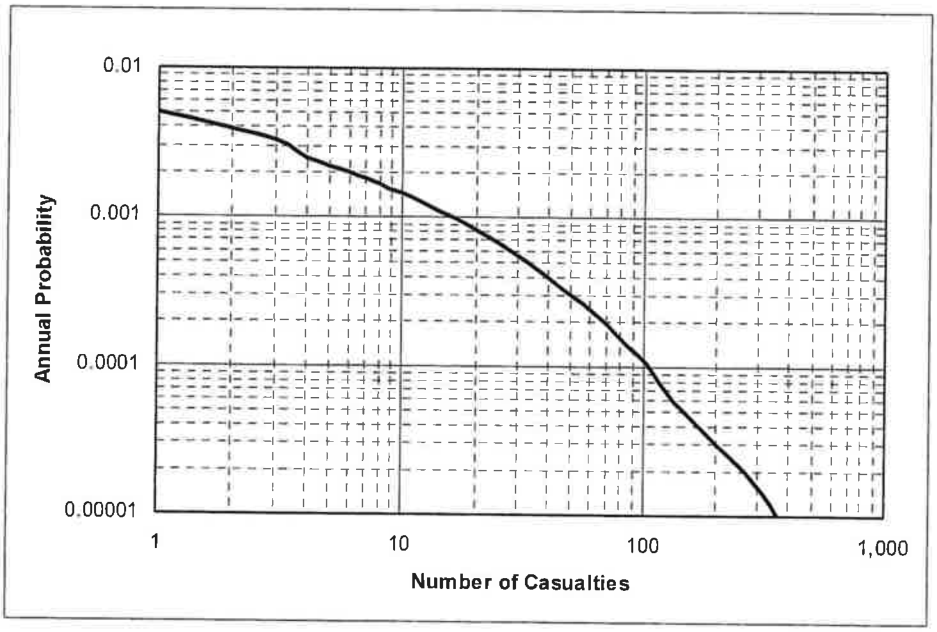

Figure 5.2 Loss curve for earthquake casualties in Christchurch. The annual probability shown is cumulative, i.e. it is the probability that a given number will be equalled or exceeded.

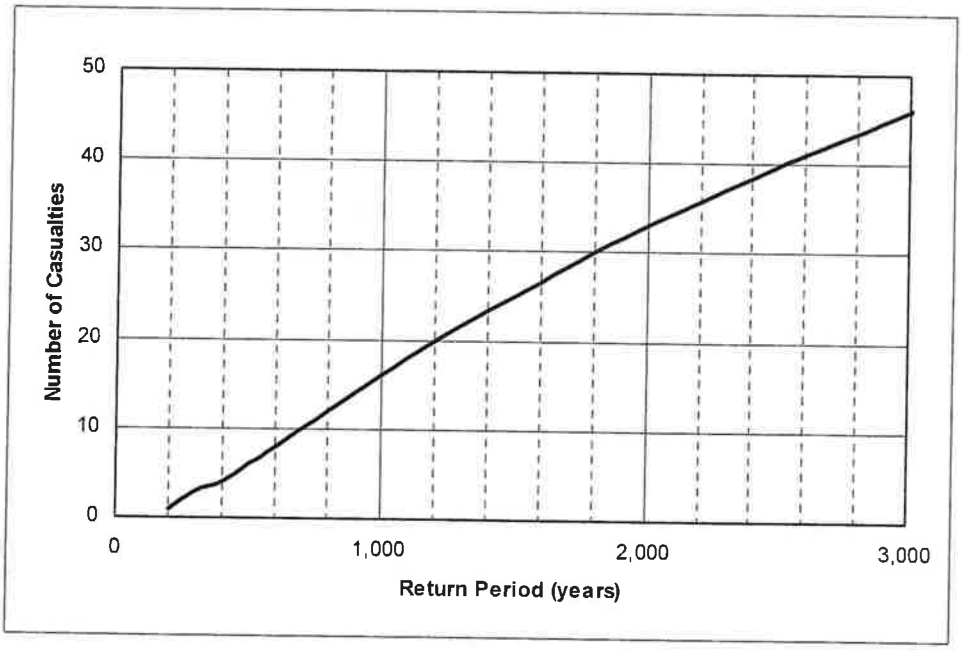

Figure 5.3 The same data as in Figure 5.2, displayed showing the casualty number will be equalled or exceeded, as a function of return period.

Table 5.3 Estimated casualties for various return periods for earthquake shaking affecting the buildings of Christchurch City.

Return Period (years)	Annual Probability of Exceedance	Number of Casualties
10	0.10	0
20	0.05	0
50	0.02	0
100	0.010	0
200	0.005	1
300	0.0033	3
400	0.0025	4
500	0.0020	6
600	0.00167	8
800	0.00125	12
1,000	0.00100	16
1,200	0.00083	20
1,500	0.00067	25
2,000	0.00050	35
3,000	0.00033	45
5,000	0.00020	70
10,000	0.00010	105

5.6 Deaggregation

It is often important to recognise which earthquake sources contribute most to the risk. For any given portfolio of assets it is possible to rank faults in order of importance using a process called "deaggregation". Table 5.4 shows the deaggregation for the 2500-year casualty rate for Christchurch, i.e. the earthquake sources that can cause 35 to 45 casualties. Distributed seismicity, i.e. earthquakes not associated with known active faults, contribute much of the risk at the 2500-year level of loss. The most important fault source is the Ashley fault which contributes one-fifth of the total risk.

Table 5.4 Earthquake sources that can cause 2500-year casualty rate for Christchurch. The right hand column represents the probability that a particular earthquake source will cause the 2500-year level of loss (35 to 45 casualties).

Source	Contribution (%)
Distributed seismicity	36
Ashley Fault	21
Porters to Grey Fault	15
Springbank Fault	12
Pegasus 1 Fault	5
Mount Grey Fault	3
Omihi Fault	3
Porters Pass Fault	3
Alpine Fault (Milford to Haupiri)	1
Pegasus 2 Fault	1

6.0 TREATMENT OF UNCERTAINTIES IN THE MODELLING

Natural variability and hence uncertainty are always present when earthquake losses are being modelled. Because we have based our modelling on a catalogue containing millions of earthquakes we have been able to address explicitly the most important sources of uncertainty. In most cases the procedure has involved generating a random number at the point of uncertainty, and then using it to select from a distribution of "adjustment" values. The forms of distribution used were "normal", for ground motion parameters, or "lognormal", for damage ratios, collapse rates, and casualty rates. Brief discussion of the various uncertainties follows.

Characteristic magnitudes of earthquakes are not known precisely. Successive earthquakes on any given fault may rupture different lengths of the fault, hence are unlikely to be of exactly the same magnitude. We take this into account by allowing the characteristic magnitudes to vary over a small range during the generation of the synthetic catalogue used to represent the seismic hazard. In the synthetic catalogue, therefore, successive earthquakes on the same fault have a range of magnitudes that are clustered around the nominal characteristic value.

Ground motion cannot be predicted with absolute confidence, because the Dowrick & Rhoades formula is obtained by fitting observed data that has a high degree of variability, and so the fit is not precise. The implication of this is that successive earthquakes on a fault will not generate identical ground motions at any particular location, even if the magnitudes are equal. There will be a distribution of intensities representing the uncertainty in the attenuation formula. This second source of uncertainty is accommodated by allowing a small variation in the ground motion as calculated for locations of interest. Two types of uncertainty are modelled, between-earthquake (standard deviation of 0.23) and within earthquake (standard deviation 0.38).

Because the buildings assets model comprises aggregated data, and not data for individual buildings, we make use of the form of mean damage ratio appropriate for aggregated data. Based on preliminary unpublished work of the author, the mean damage ratio for buildings appears to follow a lognormal distribution with a 70% probability range that is factor of 2 about the mean. This is modelled as a standard deviation of 0.3 in the logarithm (to base ten) of the damage ratio. The same factor is applied for all intensities, with the damage ratio being truncated to 1 when necessary.

Collapse is simply a particular level of damage, and so the procedure followed was the same as for damage ratio. The same procedure was also applied to the casualty rates of Table 5.1.

7.0 LIMITATIONS IN THE MODELLING

This study is essentially trying to forecast the future, and when dealing with earthquakes this cannot be done with precision. We are dependent on imperfect knowledge of past events and of future conditions. We rely heavily on the apparent robustness of taking averages of effects on substantial numbers of assets, and on models of natural phenomena that may be subject to modification as new information and interpretations become available.

The natural variability of earthquake-related processes means that there are many uncertainties in hazard and loss estimation procedures. Damage ratios for the classes of asset considered in this study are based largely on cost and value data gathered from just a few earthquakes, and so are open to refinement when empirical data becomes available from future earthquakes. The same applies even more so to rates of collapse and casualties.

We also note a need for better models of the probable earthquake responses of the various types of soil found in Christchurch. This is important because both repair costs and numbers of casualties are highly sensitive to the influence of microzonation.

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APPENDIX 1: AMPLIFICATION OF SHAKING

Comparison of observed and estimated isoseismal intensities for Christchurch. The "observed" intensities were derived from isoseismal maps [e.g. 8,31] by interpolation, and the "estimated" intensities from the New Zealand MMI attenuation model. There is an apparent tendency for the higher intensities (shaded) to be under-estimated by the model, i.e. for the higher observed intensities to be "amplified" with respect to the predictions of the model. The mechanisms for the amplification could be either or both of soft soil amplification and topographic enhancement. In our opinion this underlines a need for improved understanding of the ways in which both seismic path and local site effects influence the strength of seismic shaking in Christchurch.

Date	Time (UT)	Mw	Epicentral Distance (km)	Estimated Isoseismal MMI	Observed Isoseismal MMI	Obs – Est MMI	Obs – Est Range
16-Dec-1938	17:21	7.1	477	4.1	3.4	-0.7	-0.6 to -1.5 (est > obs)
2-Feb-1931	22:46	7.8	595	4.2	3.5	-0.7	
22-May-1948	19:21	6.4	121	4.6	4.0	-0.6	
23-Jan-1855	09:32	8.2	283	5.9	5.3	-0.6	
20-Sep-1974	19:51	5.3	43	5.0	4.5	-0.5	-0.5 to +0.5
11-Jul-1986	23:03	5.4	52	4.8	4.5	-0.3	
24-Nov-1995	06:18	6.3	92	4.8	c. 4.5	c. -0.3	
1-Aug-1942	12:34	7.0	384	4.2	4.0	-0.2	
9-Mar-1929	10:50	7.0	101	5.6	5.4	-0.2	
18-Jul-1876	16:47	6.0	409	4.3	4.2	-0.1	
11-Feb-1893	20:30	6.9	332	4.1	4.0	-0.1	
15-Oct-1848	14:10	7.8	233	5.6	5.5	-0.1	
18-Oct-1868	12:35	7.2	360	4.1	4.1	0.0	
11-Apr-1965	00:11	6.1	148	4.2	4.3	0.1	
22-Mar-1995	19:43	6.1	304	4.3	c. 4.5	c. 0.2	
10-Jan-1951	19:15	5.9	94	4.6	4.8	0.2	
4-Jun-1869	20:30	5.0	c. 2	**7.2**	**c. 7.5**	**c. 0.3**	
31-Aug-1870	00:00	5.6	26	**5.9**	**6.2**	**0.3**	
4-Dec-1881	19:37	6.0	77	5.0	5.3	0.3	
18-Jun-1994	03:25	6.7	106	5.2	5.5	0.3	
27-May-1992	22:30	5.9	227	4.2	c. 4.5	c. 0.3	
25-Dec-1922	03:33	6.4	66	**5.8**	**6.2**	**0.4**	
31-Aug-1888	16:45	7.2	107	**5.8**	**6.2**	**0.4**	
16-Jun-1929	22:47	7.7	207	5.4	5.8	0.4	
15-Nov-1901	20:15	6.8	107	**5.5**	**6.0**	**0.5**	
23-May-1968	17:24	7.2	205	4.9	5.5	0.6	0.6 to 1.5 (est < obs)
26-Jun-1946	12:34	6.3	111	4.8	5.5	0.7	
8-Mar-1987	19:17	5.4	c. 58	**c. 4.8**	**6.5**	**c. 1.7**	> 1.6

Institute of Geological & Nuclear [illegible]

Gracefield Research Centre
69 Gracefield Road
PO Box 30 368
Lower Hutt
New Zealand
Phone +64-4-570 1444
Fax +64-4-570 4600

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
Phone +64-3-477 4050
Fax +64-3-477 5232

Rafter [illegible]
[illegible]
PO Box [illegible]
Lower Hutt
New [illegible]
Phone [illegible]
Fax [illegible]

[illegible]
State [illegible]
[illegible]
Taupo
New [illegible]
Phone [illegible]
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