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Modern Multi-Storey Buildings and Moderate Earthquakes

A Research Project for the Earthquake Commission
EQC Project No. 93/173

by

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Summary

Recent *moderate* earthquakes overseas have highlighted that the combined cost of direct damage and indirect costs from such events can be significant. In the case of multi-storey buildings the non-structural damage is likely to be considerable, such that the repair and reinstatement process will take a long period of time and involved extensive occupancy disruptions.

This project integrates recent work from a number of different sources to enable a realistic *moderate* earthquake scenario to be portrayed, and foreshadows the likely impacts and process issues.

Key Issues Examined

1. Characterising moderate earthquakes in terms of parameters used in the engineering design of new buildings
2. Quantifying the level of lateral drifts anticipated for modern multi-storey buildings
3. Identifying the non-structural damage that could potentially be caused by such movement
4. Highlighting the major issues and likely durations associated with the damage assessment and repair process

Principal Findings

- A moderate earthquake can be characterised as one that generates MM8 intensity on intermediate soils. In Wellington, such an event is considered to be represented by a magnitude 6.0 to 6.5 earthquake which has a return period of approximately 140 years (probability of occurrence 30% in 50 years).
- The maximum likely interstorey drift of a 13 storey moment resisting frame building designed to NZS 4203:1984 in such an event was found to be 10 to 15mm, and the corresponding local displacement ductility demand between 1.5 and 2. This indicates that a moderate earthquake is likely to cause structural damage to a number of buildings of this type, in addition to extensive non-structural damage.
- The likelihood of structural damage occurring under MM8 shaking contrasts with the qualitative damage descriptions for the lower values of the MM scale, whereby damage is not implied to modern construction until higher levels of shaking.
- Damage ratios that are commonly applied to modern multi-storey buildings for MM8 intensity shaking are around the 6 to 8% level. First principles assessments based on the above drift levels are used to suggest that ratios of 7 to 30% may be more appropriate. This indicates that typical damage ratios for moderate earthquake intensities represent lower bound damage estimates only.
- Consideration of the insurance and engineering processes for damage assessment and repairs following earthquakes has highlighted that even for buildings sustaining non-structural damage, there are a number of interactive steps involved. These steps can involve owners and tenants with separate but inter-related building, contents and business interruption policies. Analysis of the impact of the likely interaction plus the disruptive effect of repairing non-structural damage has indicated that some multi-storey buildings could take between 5 and 7 weeks before full re-occupancy can be assured.

- An empirical approach for assessing indirect losses for businesses operating in modern multi-storey buildings has been developed. While further development of this methodology is required, it is thought to be of value to tenants in establishing the level of business interruption cover they should have in place.
- An indicative descriptive scenario which emphasises the human reaction to and impact of a moderate earthquake is also included.

Recommendations

General

- There needs to be a better awareness of the level of damage and disruptive impact of earthquakes that are smaller than "design" events but correspondingly more likely to occur
- The limited protection to non-structural and contents elements in moderate earthquake events afforded by modern ductile frame structures needs to be more clearly conveyed by designers to owners and prospective tenants. This category of construction is essentially untested in terms of actual earthquake exposure in New Zealand.

Specific

- A working party comprising insurance adjusters and earthquake engineers be established to map the claims process for commercial premises following earthquakes, and to identify prior training needs and post-event guidance requirements for the engineering profession and the insurance industry.
- Given the extensive use of the MM scale in the analysis and description of historical earthquakes, an improved set of damage descriptors for modern buildings under MM8 and MM9 shaking in terms of both non-structural and structural performance should be developed.
- The findings from this study in terms of structural performance parameters should be further examined with regard to the frequency and duration of shaking from the scenario spectra. This aspect could involve the application of appropriately scaled time history earthquake traces to sample buildings.

1. Introduction

1.1 Project Origins

For community planning purposes and for the design of new buildings, emphasis is traditionally placed on the cost-related aspects associated with survival and reconstruction following large earthquakes. While this is entirely appropriate, there is also a need for the physical and operational effects of lesser but more likely seismic events to be given due consideration.

Recent moderate earthquakes overseas (Loma Prieta, Newcastle, Northridge) have highlighted that the combined cost of direct damage and indirect costs resulting from the disruption which follows such events can be much greater than generally anticipated. Furthermore, the methodology for obtaining estimates of indirect losses from either moderate or major earthquakes is much less well-established than for loss estimates relating to physical damage.

This is of particular importance to New Zealand given the lack of significant earthquakes affecting major urban centres since the 1931 Napier earthquake. The corollary of this is that the next moderate earthquake to strike a metropolitan area is likely to have a community impact much greater than the earthquake engineering fraternity might anticipate. While this would be principally due to a lack of familiarity with post-earthquake processes, it is the contention of the authors that damage levels to building and other structures is likely to be greater than predicted by traditional damage ratio approaches.

Over the past decade, designers and planners have been provided with “tools” by way of serviceability limit state criteria and hazard scenarios with shorter return periods to address the issue of *moderate* earthquakes. However the advent of serviceability limit state design of buildings for earthquake is relatively recent, and the criteria are still only in their formative stages. Also, the reality is that most of the multistorey buildings constructed in the “boom” period of the 1980’s were designed with only passing regard to the physical consequences of a moderate earthquake. The majority of buildings in this category are flexible moment-resisting frame structures, and can be expected to experience considerable drift in even moderate earthquake shaking.

The “bigger picture” beyond the specific consideration of damage to modern multi-storey buildings is the extent of the recovery and reconstruction process following a moderate earthquake. The likely consequence of the considerable non-structural damage from such an event is that the process is likely to take longer and be more disruptive than generally anticipated, with associated cost implications.

The various lifelines engineering studies carried out in New Zealand since 1990 (***CAE***, 1991; ***WELG*** 1993, 1994, 1995) have resulted in a clearer picture of the level of post-earthquake disruption due to lack of water, power, gas and telecommunications services. Realistic scenarios for the purpose of assessing likely disruption periods and hence costs can now be created with more confidence.

1.2 Aim and Objectives

The aim of this study was to explore the issues associated with the likely impacts of moderate earthquakes on modern multi-storey frame buildings, and highlight areas where further consideration should be given.

The project objectives as stated in the original submission were as follows:

(1) To assess the financial impact of moderate earthquakes on the structure, contents and business interests of the occupants of a representative sample of modern New Zealand multi-storey buildings.

(2) To develop the basis of a methodology which can be used to estimate the direct and indirect costs of reinstating any given building or facility subjected to a moderate earthquake.

(3) To formulate an engineering opinion as to the adequacy of protection provided to modern multi-storey buildings against the effects of moderate earthquakes by current design and construction detailing philosophies.

Initial project work identified that full coverage of each of these elements would involve much more time and resources than originally anticipated. The project was subsequently re-focused to examine the key issues associated with these objectives, and to indicate a direction for further research in this area to follow.

The broader purpose of this project has been to promote a change in emphasis for earthquake preparedness from major to moderate earthquakes. This in turn, it is hoped, will instill a greater sense of urgency in the business community with regard to business continuance planning. An associated outcome will hopefully be heightened awareness of the need for a better understanding of the respective roles of insurers and engineers following earthquakes.

1.3 Key Issues

The key issues on which this report focuses are:

1. Characterising moderate earthquakes in terms of parameters used in the engineering design of new buildings
2. Quantifying the level of lateral drifts anticipated for modern multi-storey buildings
3. Identifying the non-structural damage that could potentially be caused by such movement
4. Highlighting the major issues and likely durations associated with the damage assessment and repair process

1.4 Project Methodology

This project involved the following steps.

1. A literature review of articles relating to recent moderate overseas earthquakes
2. Characterisation of a moderate earthquake in terms of intensity and acceleration parameters
3. Review of damage ratios for modern ductile multi-storey concrete frame buildings
4. Physical inspection of two modern ductile multi-storey concrete frame buildings designed in accordance with NZS 4203: 1984
5. Analysis of one of these buildings using the parameters obtained from Step 2 to identify the likely order of drift in a moderate earthquake
6. Consideration of the level of damage resulting, and comparing this against conventional damage ratios
7. Consideration of the recovery scenario, including the time implications associated with the assessment and repair process

2. Literature Review

2.1 General

This section summarises key comments extracted from various articles reviewed, and groups them under appropriate categories.

The comments in this section are intended to provide general background; specific references are also included in subsequent sections.

2.2 Scale of Impact

Arnold (1991) noted that while the overall incidence of spectacular and life-threatening non-structural damage due to the 1989 Loma Prieta earthquake was small, the <u>total value</u> of the damage was high. Thousands of buildings suffered damage to gypsum board partitions, to suspended ceilings, to wall and floor finishes, and to roof-top equipment. The causes of this damage, whether structurally related or not, were apparently little studied. While he observed that reports for damage claims do not reveal the origin of damage, a number of statistical studies have revealed some useful patterns of loss. The Building Owners and Managers Association (BOMA) of San Francisco surveyed 129 medium and large offices; of these buildings, 9% suffered structural damage, while 86% suffered non-structural damage. The median dollar value of damage per building was $94,120. Of this, $66,500 or 70% was water damage. This was categorised as $50,000 sprinkler related, $5,000 water supply related, and $11,500 HVAC related.

The remainder of the median damage was divided into:

Immediate clean-up:	$16,000
Elevators:	$ 3,080
Mechanical:	$ 3,540
Computer-related:	$ 5,000

The study also noted that 87% of the respondents reported elevator disruptions. This averaged 35 hours, but for the most part was due to power outages in San Francisco. Loss of service time varied from 4 hours to 3 weeks.

To illustrate the severe nature of water damage, Arnold quotes from the reported description of a building damaged in the Whittier Narrows earthquake of 1987:

> *"Losses from non-structural elements within the building far exceeded the structural damage, with water damage to the building interior from the fire suppression system one of the major losses. Smoke detectors, tripped either by dust suspended in the air from falling debris, or from short circuits created as the detectors collapsed with the suspended ceiling, resulted in the main deluge valve of the dry system opening, spraying water from fire sprinklers throughout the office areas."*

Harris (1991) reported on a study of fire protection system performance after the 1989 Loma Prieta Earthquake. Telephone surveys were made of several dozen city, government, insurance agencies, and large industrial sites to obtain qualitative and quantitative data on fire system performance. Detailed data was collected from post-earthquake engineering reports and from site visits and inspections of about a dozen large facilities. Where possible, data on fire protection failures were de-aggregated from sites associated with structural damage or ground settlement induced contributory damage to interior piping.

Fire protection failure was considered to result from all reported causes that affected system function. This included breakage of piping, sprinkler head damage, and actuation of dry systems among others. All data, both success and system failures, were assigned to regions of MM ground motion intensities between VI and IX. The results of this study indicate that failures are in the range of 5% to 10% of installed systems in areas with MM intensities of approximately VII to VIII. Failure rates tended to increase with increasing MM intensity. Overall, system performance has been comparable to the 1971 San Fernando experience.

Most failures were of a localised extent, quickly repaired and of minor consequence. Fortunately, few post-earthquake fires occurred, thereby limiting the consequences of individual failures. Some specific failures have, however, resulted in multi-million dollar losses to building owners and occupants. These have been the result of water damage to structures, building contents, electrical power, controls, computer, and high value goods in storage.

2.3 Damage Ratios

Dowrick and Rhoades (1995) reported on an analysis of the level of damage sustained by contents and equipment in the Edgecumbe earthquake. They categorised each item (or parcel) as being either *robust, medium or fragile*, noting that the situation of an item may affect its vulnerability (eg. secured or unsecured). In this study, most office equipment was classified as *medium* vulnerability.

The results suggest that at MM9 intensity, earthquake protection of equipment could reduce the damage levels by about an order of magnitude for unprotected highly vulnerable equipment. This factor increases at MM7, reflecting that the <u>threshold intensity of shaking for damage to occur</u> to *fragile* items is lower than for *robust* items.

The proportion of items (or parcels) damaged is also a useful parameter. At MM9, 62% of *fragile* equipment parcels were damaged compared to 40% of *robust* equipment parcels.

Whilst noting that mean damage ratios for all types of buildings in the Edgecumbe earthquake are lower than previously assumed, Dowrick and Rhoades also found that mean damage ratios did not show any significant reduction for buildings of more modern construction, contrary to expectation.

For the 1986 San Salvador earthquake, ***Tiedeman*** (1992) reports that 26 buildings with no structural damage produced mean damage ratios of 30%.

2.4 Probabilistic Approach

The HAZUS loss estimation methodology (***National Institute of Building Sciences***, 1997) has been developed to produce loss estimates for use by agencies involved in planning for earthquake mitigation, emergency preparedness and response and recovery.

This probabilistic methodology features GIS-based software, and was developed during the mid-1990's (concurrently with this project).

The process is structured to work from building damage through to other physical aspects such as non-structural elements and extending on to induced physical damage (inundation, fire, debris), and direct and indirect economic losses.

Sixteen basic model building types reflecting common construction materials and lateral force resisting systems are defined. Damage states of *none*, *slight*, *moderate*, *extensive*, and *complete* are defined in qualitative terms for each building type.

Process input consists of (i) building type/ characteristics and (ii) seismic design levels or level of ground shaking or deformation. The principal form of output is fragility curves which are estimates of the cumulative probability of being in or exceeding each of the defined damage states for a given level of shaking (or ground deformation). From these curves, the probability of the building or contents being in one of the damage states can be established.

2.5 Estimation of Damage to Contents

Clark (1993) presented the results of a comprehensive analysis to establish the dynamic response of a specific building and its contents. Of particular interest to this study was *firstly* the process of estimating floor displacements, velocities and accelerations, and *secondly*, the establishment of relationships between floor velocity and acceleration and the rocking and overturning of building contents.

This study covered the full range of earthquake magnitudes, and developed a continuous relationship between peak accelerations and return periods. This relationship enables damage scenarios to be compiled for increasing return period events.

The following categories of contents items were modelled as rectangular shaped rigid bodies:

- file storage units and storage cabinets
- book cases
- computer hardware cabinets
- PABX units
- power switchboard cabinets

Tables for object stability were developed.

2.6 Legal Context in New Zealand

Recent legal developments in New Zealand relating to the roles and responsibilities of company and property owners have also led to an increase in awareness of earthquake issues.

The Health and Safety in Employment Act (1993) focuses on safety in the workplace. The prospect of unsecured equipment (filing cabinets, computers, etc) falling on and injuring staff in even a moderate earthquake has caused many companies to implement programmes to secure office equipment. This has been assisted by the publishing in 1994 of the New Zealand Standard for Seismic Securing of Equipment, NZS 4104.

The Companies Act (1993) addresses the obligations of company directors to take all reasonable steps to ensure the continuing viability of their organisation in the face of forseeable events. Failure of a business following an earthquake due to lack of insurance or business continuance plans, for example, come within the scope of this Act. The assessment of hazards due to an earthquake event and the mitigation of those hazards comes within the scope of the Health and Safety in Employment and the Companies Acts.

In order to avert liability under both of these acts, owners and directors must be able to demonstrate that they have taken positive and continuing action.

3. Characteristics of a Moderate Earthquake

3.1 General

It is acknowledged that the term "moderate earthquake" is to an extent conceptual, and lacks formal definition. This section seeks to characterise a moderate earthquake in both general terms (ie. modified Mercalli scale) and specific terms (ie. engineering design parameters).

3.2 Modified Mercalli Scale

The Modified Mercalli scale (MM) is a subjective measure of the intensity of earthquake ground shaking based on personal observations. As such, it has limited application in quantifying ground shaking measurements, with increasing emphasis being placed on parameters such as displacement, velocity and acceleration (eg. peak ground acceleration). The historical emphasis on early construction also causes difficulties in applying the MM scale to modern construction. ***Paulay and Priestley*** (1992) observe that the expected performance of well-designed modern buildings cannot be directly related to modified Mercalli intensity. The usefulness of the MM scale with regard to modern reinforced concrete buildings has also been questioned in the field of post-earthquake reconnaissance (***Brunsdon*** 1993). A linkage with the MM scale is however necessary as it continues to provide important linkages to historical data which use damage ratios to form the basis for loss estimates.

Care needs to be taken when making reference to the MM scale. Terms in Roman figures (eg. MMVII, MMVIII etc) generally refer to the contour bands of discrete intensity levels of shaking, while terms in Arabic figures refer to a continuous scale of intensity of shaking. The latter has become necessary for computational modelling purposes.

The following diagram illustrates how these different conventions relate:

Conventional Mercalli Intensity		VI		VII		VIII		IX	
Continuous MM Function	6.0		7.0		8.0		9.0		10.0

In some quarters, the definition of a moderate earthquake can be taken to encompass the range upper MM VII to lower MM VIII (ie. MM 7.5 to MM 8.5). However the use of whole numbers on the MM scale is preferred for the purposes of referring to damage ratios. Accordingly, and given the lack of precision in the MM scale in this range of damage with regard to modern multi-storey buildings, this difference in definition is not considered to be of significance for the purposes of this project.

A revision of the MM scale to take greater account of modern construction (***Smith*** et al 1992) indicated the following likely damage for MM 8:

- *Buildings Type III* (designed to resist earthquakes but without special damage limiting measures ie. mid 1930's to mid 1970's) *damaged in some cases*
- *Some pre-1965 infill masonry panels damaged*
- *A few post-1980 brick veneers damaged*
- *Houses not secured to foundations may move*

While no mention of the likely performance of post-1980 multi-storey buildings is made under MM 8, *"damage or permanent distortion to some buildings"* is indicated for these buildings under MM 9.

An extract from a Californian modification to the MM scale which emphasises non-structural damage issues (***FEMA 74***, 1985) indicates that the following damage could be anticipated from a MM 8 earthquake:

> *"Suspended ceilings without diagonal bracing partially fall. Spring mounted mechanical equipment without seismic restrainers breaks supports and falls. Pipes may leak in buildings. Tall unanchored shelving and storage racks lose contents or tip over".*

Dowrick (1996) has proposed a development of the descriptions for higher MM intensities which builds upon the earlier work by Smith et al. This work includes the addition of a set of performance indications for buildings from the capacity design era (ie. the same set as the subject of this study). In this proposal, no performance indication is given for MM8 intensity. For MM9 the following damage description is given:

> *"Damaged in some cases, some flexible frames moderately".*

For the purposes of this study, a moderate earthquake is taken as one that produces a peak intensity on intermediate soils (as defined in NZS 4203:1992) of level 8 on the Modified Mercalli scale.

Given the extensive use of this scale in the analysis and description of historical earthquakes, an improved set of damage descriptors for modern buildings under MM8 and MM9 shaking in terms of both non-structural and structural performance is clearly warranted.

3.3 Moderate Earthquake Scenario for Wellington

As part of this project, the Institute of Geological and Nuclear Sciences was commissioned to prepare a moderate earthquake scenario for Wellington. This scenario is outlined in detail by ***McVerry*** (1996), with a summary of the key findings presented in this section.

The purpose of the study by the Institute of Geological and Nuclear Sciences was to define magnitude and distance combinations corresponding to a “moderate earthquake” in the Wellington region, and to provide corresponding 5% damped elastic response spectra.

This study identified that an earthquake of magnitude 6.0-6.5 at a depth of 10-30 km at some unspecified location up to 40 km from central Wellington is representative of a scenario for a "moderate" earthquake in Wellington. Such an earthquake is estimated as likely to cause peak ground accelerations over a large part of the region of about 0.2g on rock, which may be amplified to about twice this value at some soil sites. The probability of a shallow earthquake of magnitude 6.0-6.5 within a horizontal distance of 40 km of Wellington city is estimated as 30% in 50 years, corresponding to an average recurrence interval of 140 years. No such event is known to have occurred in this region since 1840, but several precedents in regions with analogous tectonic regimes have occurred in recent years, such as the 1990 Weber and 1993 Ormond earthquakes. The June and August 1942 Wairarapa earthquakes both generated felt intensities of MM6 and 7 in Wellington City and the Hutt Valley respectively ***Dowrick*** (pers. comm.).

This scenario is consistent with the regional event scenario used in a recent study of lifelines in Wellington (***WELG***, 1993). It represents a larger event than the Scenario 1 earthquake developed by the Wellington Regional Council (***Kingsbury and Hastie***, 1992).

Elastic response spectra for 5% damping were estimated for rock, stiff (intermediate) soils and deep soils for the scenario events (refer Table 3.1). Depending on site conditions, the amplitudes of the peaks of the estimated spectra reach between 50% and 94% of the peaks of the NZS4203:1992 code spectra, falling to lower ratios at longer spectral periods (refer Figure 3.1). The spectra exceed the serviceability levels of the code, for which no structural damage and minimal non-structural damage is expected.

Table 3.1: Elastic Spectra for a Moderate Earthquake in Wellington *(McVerry 1996)*

	ACCELERATION RESPONSE SPECTRA SA(T) (g) 5% damping		
Period T(s)	**ROCK**	**INTERMEDIATE SOIL**	**SOFT OR DEEP SOIL**
0.0	0.20	0.30	0.40
0.10	0.50	0.60	0.76
0.18	0.57	0.85	1.03
0.2	0.55	0.88	1.05
0.3	0.46	0.91	1.12
0.35	0.38	0.88	1.13
0.5	0.29	0.64	1.01
0.7	0.20	0.48	0.81
1.0	0.126	0.33	0.59
1.5	0.070	0.20	0.37
2.0	0.046	0.138	0.27
3.0	0.025	0.083	0.16

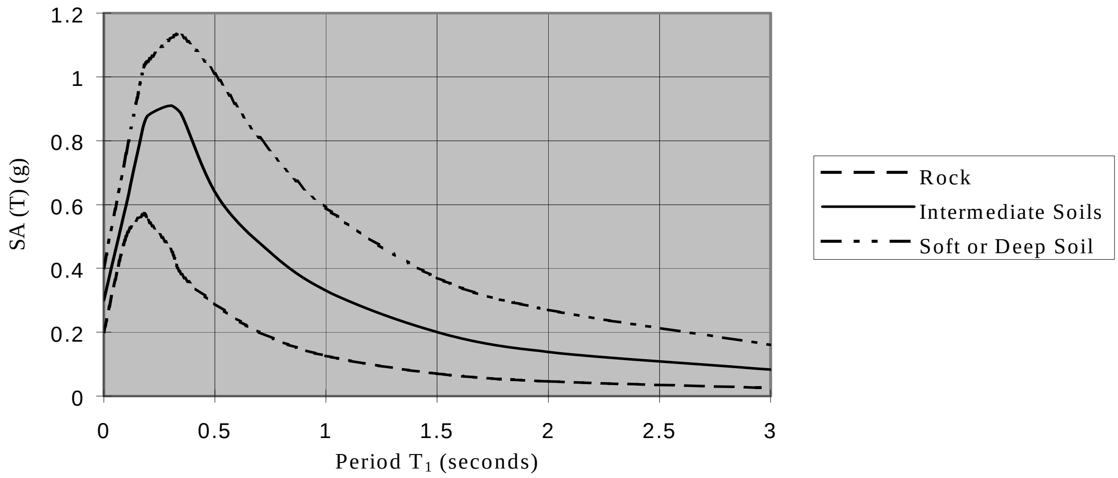


***Figure 3.1: "Moderate" Elastic Spectra for Wellington** (McVerry 1996)*

The estimated 5% damped elastic response spectra are considered to meet the requirements for a moderate, but damaging, earthquake. They lie between the spectra for the code serviceability limit state, for which no structural damage and only minimal non-structural damage is prescribed, and the ultimate limit state, for which some structural damage is acceptable but collapse and irreparable damage is to be avoided.

4. Damage Ratios and Insurance Issues

4.1 General

The estimation of *direct* losses (structural, non-structural and contents) is catered for principally by damage ratios. There is however significant interaction between *direct losses* and *indirect losses* relating to *business interruption*.

In considering this interaction, there is a need to acknowledge the different insurance perspectives of property ownership and tenancy. In simplistic terms, the *tenant* sustains physical damage to contents and business losses, whereas the *owner* sustains damage to tenancy-related structural and non-structural elements (partitions, ceilings and finishes). Table 4.1 below groups the affected parties by loss category.

Table 4.1: Loss Category and Affected Parties

	Loss Category (1)	(2)	(3)	(4)
	Damage to Structure *(beams, columns, structural walls)*	**Damage to Non-structural items *(partition walls, ceilings, glazing, building services)***	**Damage to Contents *(furniture & shelving, equipment)***	**Business Interruption *(loss of profit[1], loss of rent[2])***
Affected Parties	Building Owner	Building Owner (Tenant)	Tenant (Building Owner)	[1]Tenant [2]Building Owner

The ownership of these items in certain tenancy situations may not be clearcut (e.g. ceilings and partitions that form part of specific fitouts), thereby giving rise to practical insurance process issues. These issues are likely to assume greater significance for multi-storey buildings in moderate earthquakes than in more damaging events.

This section provides a brief overview of the process issues associated with the application of damage ratios for direct loss, and to the estimation of indirect losses.

4.2 Damage Ratios For Direct Losses in Moderate Earthquakes

Damage ratio is defined as:

$$Dr = \frac{\text{Cost of Damage to Property}}{\text{Value of Property}}$$

where 'value of property' can be variously defined as *Replacement Value*, *Market Value*, *Indemnity Value* or *Insured Value*. Replacement value is preferred because it is more easily estimated and more consistent in its definition.

Mean Damage Ratio is typically defined as the <u>value of *direct losses* sustained by a group of buildings as a proportion of the replacement value.</u> Mean Damage Ratio is that taken *across a given MM intensity zone*. Accordingly, there are difficulties in applying DRs to individual buildings.

Damage Probability Matrices indicate the likely variability of damage about the mean. These include non-structural damage, and this represents a large proportion of the total damage. It is important to realise that damage to non-structural components will occur at earlier levels of intensity to that of the structure and will reach a saturation level, beyond which their damage will rise only slightly.

A wide range of damage ratios were developed in the United States by the Applied Technology Council (***ATC 13***, 1985). This work was based on statistical analysis of expert opinion data, as there is little real data for damage ratios for specific building types.

In Table 4.2 following, the Mean Damage Ratios for medium and high rise modern ductile concrete framed buildings are summarised (expressed as a percentage, taken from ATC13). The values in this table indicate that the difference between the medium and high rise building size categories is not significant.

"Direct loss" in the above context is taken to include *all* physical damage including structure, fabric and services <u>plus the loss or damage to building contents</u>, but excludes the value of loss of function or lost business opportunity.

Damage ratios are therefore effectively *overall* ratios for any given building or group of buildings. In practice, they are not broken down into the sub-categories of *Structural*, *Non-structural*, and *Contents*. This is primarily because insurance data from previous earthquakes is typically aggregated at an individual risk level (ie. building level) or risk category level (ie. Contents).

This reflects the varying level of detail supplied to insurers by owners and tenants, with fully broken down schedules being rarely provided.

Accordingly, the application of such ratios at a detailed level is quite limited, particularly given that the first two of these sub-categories relate principally to the owner, whereas the latter is the domain of the tenant.

Table 4.2: Mean Damage Ratios for Modern Ductile Concrete Frames

	Modified Mercalli Intensity						
	VI	VII	VIII	IX	X	XI	XII
Medium Rise *(4 – 7 storeys)*	3.1	4.9	6.2	13	19.1	29.9	40.1
High Rise *(8 storeys or more)*	4	4.9	7.5	16.1	22.5	33.8	40.3

4.3 Indirect Losses: Parameters for Loss of Function

The processes for estimating indirect losses are not well established for either moderate or major earthquakes.

Loss of function and *time for restoration* are typically treated simultaneously. Specific factors affecting the loss of function (or usability) of a facility are:

- Direct damage ***to*** the facility (structural and nonstructural) and equipment damage ***at*** the facility (contents)
- Personnel loss
- Damage to lifelines ***at*** a facility
- Damage to lifelines ***serving*** a facility
- Interruption of material supplies, replacement parts and services to the facility

The latter two represent effects external to the facility; loss of function and restoration time are particularly sensitive to the failure of lifeline systems. Personnel loss for moderate earthquake events is not considered to be significant.

A methodology for evaluating the impact of lifeline failures on loss of function is outlined in ATC 13. It is based on separate consideration of *main components* (eg. bulk water storage), *distribution components* (water mains > 600 mm) and *service components* (street mains).

The estimations for loss of function and restoration time were derived by the same expert opinion approach as used in the damage probability matrices in the rest of the document.

In addition to the degree of damage, the availability of personnel, resources, supplies, replacement parts, services and the rapidity with which building permits can be issued are the key factors in the restoration of function.

The paucity of data currently available on loss of function precludes statistical analysis of information from past events.

It is understood that indirect losses are rarely the subject of a systematic estimate during the process of taking out such cover. Normally a dollar value relating to annual profits is agreed upon between the insured and insurer, and written into the policy along with a time limit.

As part of this project, consideration was given to developing an empirical approach for assessing indirect losses in multi-storey buildings. A possible approach is outlined in ***Appendix 1***, with emphasis being placed on identifying the key parameters and a basis for quantifying them. The objective of the methodology is to be able to make a broad estimate without needing to obtain detailed commercial information.

A sample application of this approach to the case study building (refer following section) is included.

While further development of this methodology is required, it is thought to be of value to tenants in establishing the level of business interruption cover they should have in place.

4.4 Extent of Business Interruption and Office Contents Cover Held

As a part of this study, an attempt was made to identify the proportion of offices in New Zealand that currently hold Business Interruption cover, along with those that may have inadequate or non-existent contents cover.

These figures proved difficult to establish, as the information is held at the level of individual insurance companies, and not aggregated nationally.

It is however estimated that virtually all offices have some form of contents cover.

5. Structural Response of a Multi-Storey Building to a Moderate Earthquake: A Case Study

5.1 General

Two multi-storey moment resisting frame buildings that had been designed to the previous loadings standard (NZS 4203:1984) were inspected in order to qualitatively assess their likely response to a moderate earthquake. Following this initial appraisal, one of these buildings was selected for re-analysis in accordance with NZS 4203:1992, using the moderate scenario from Section 3.3 as seismic load inputs.

The purpose of this analysis was to establish the level of drift and implied ductility demand that such a building is likely to experience in comparison with serviceability and ultimate limit state events.

This section describes the case study building and the analysis process, and summarises the structural response to the moderate earthquake scenario.

5.2 Description of Case Study Building

A thirteen storey moment-resisting concrete frame building constructed in Wellington in 1988 was chosen as a case study example for this project. It is both vertically and horizontally regular, and constructed in a predominantly precast form that was common to this era.

The structural design features are summarised in Table 5.1 following.

The building was designed in 1987 using ETABS version 4 as the principal analysis tool. As with the majority of concrete frame structures designed in New Zealand, the design was governed by interstorey drift considerations. In this case, the critical interstorey drift was between ground and first floor; the limit of 0.01H from NZS 4203:1984 required a 48mm maximum drift for this level, and 36mm for upper floors.

Table 5.1 : Design Features Summary for Case Study Building

Date of Construction:	1988		
Number of Storeys:	13 (plus one plant level)		
Overall Typical Floor Dimensions:	Regular Octagon with 20m between parallel sides		
Gross Floor Area:	400m^2 (typical)		
Approximate Net Floor Area:	350m^2		
Inter-Storey Heights:	Ground to First Floor:	4,780mm	
	Subsequent Floors:	3,600mm	
Structural Form:	Reinforced concrete perimeter frame for lateral load resistance.		
	Reinforced concrete internal secondary frames for gravity load resistance.		
	Foundation:	1500mm thick raft	
	Floor System:	Dycore plank with 65mm topping.	
Member Sizes: (35MPa)	Exterior Frame:	Columns: Beams:	600 x 600 nominal (8No.) 900 x 500
	Frame in Front of Lifts:	Columns: Beams:	600 x 450 (2No) 450 x 450
	Central Frame:	Columns: Beams:	750 x 750 (1No) 750 x 750

5.3 Structural Analysis Process

A modal response spectrum analysis was carried out on the building structure in accordance with NZS 4203: 1992, modified by the use of a “Moderate” earthquake response spectra as developed for this study by McVerry (1996). The objective was to determine interstorey displacements, hence potential for non-structural damage due to a moderate earthquake.

NZS 4203: 1992 superseded the 1984 edition that was current in 1987 when the building was designed. The major change from the 1984 to the 1992 code was that a “limit state” format was introduced. There were also changes to the way the spectra were modified to take into account “ductility” and site “soil conditions”. These changes did not have a material effect on the results of the analysis as can be seen from Table 5.2 below which compares the seismic design coefficients for the “Ultimate Limit State” and equivalent in the older code (“flexible” subsoils were used given that the 1984 version of NZS 4203 had “rigid” and “intermediate” listed together).

Table 5.2: Comparison of Seismic Design Coefficients

NZS 4203: 1984	NZS 4203: 1992
C_d = CRSM where : $C = 0.0825$ for $T = 1.8$ sec flexible subsoils $R = 1.0$ $S = 0.8$ $M = 0.8$ $C_d = 0.053$	$C(T) = S_m C_h(T,1) S_p R Z L_u$ where : $S_m = 0.17$ for $\mu = 6$ & $T > 0.7$ sec $C_h(T,1) = 0.44$ for $T = 1.8$ sec flexible soil sites $S_p = 0.67$ $R = 1.0$ $Z = 1.2$ $L_u = 1.0$ $C(T) = 0.060$

Figure 5.1 plots the elastic acceleration spectra for intermediate soil sites for the serviceability and ultimate limit states along with the McVerry moderate scenario.

For "Intermediate Soil Sites" the McVerry moderate earthquake spectral curve lies close to midway between the SLS and ULS curves of the 1992 Code at a period of T=1.8 seconds. The *Intermediate* soil response was considered appropriate for the structure under consideration with a location close to the original shoreline of Wellington's Te Aro area. The equivalent $C_h(T,1)Z$ value was used in the analysis to determine the building interstorey displacements under a "Moderate" earthquake.

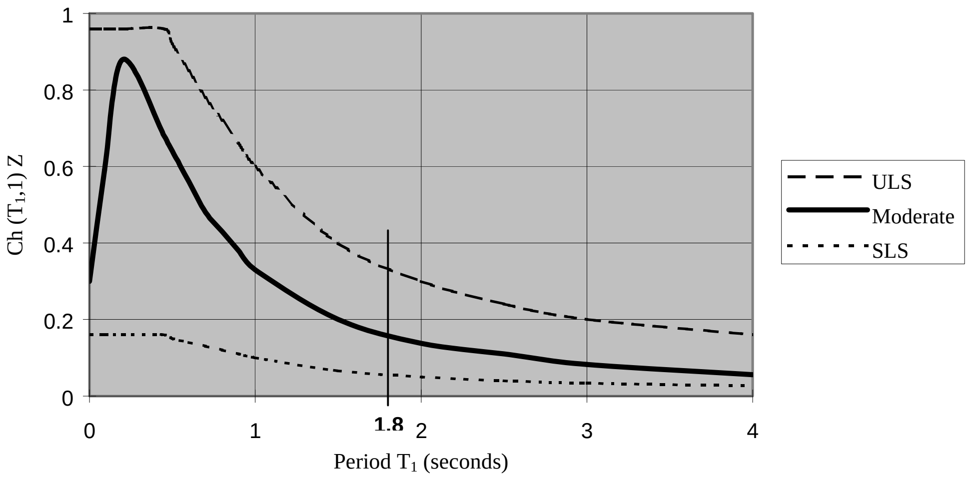


Figure 5.1: Elastic Acceleration Response Spectra for Intermediate Soil Sites (Z=1.2)

This dynamic modelling of the 13 storey perimeter frame structure utilised the ETABS, version 5.11, computer software package. The octagonal frame members were set up in 12 bays with a rigid diaphragm at each floor. Column and beam members were given a sectional moment of inertia of 0.7 I_{gross} to model cracked stiffness. This gave a computed first mode period of 1.84 seconds, compared to 1.7 seconds from the 1987 analysis with corresponding member cracking allowances and 1.65 seconds for the full gross section. For the first 10 modes more than 90% of the input building mass was participating. As is the case for design, this analysis assumed full separation of non-structural elements.

The "Moderate" earthquake response spectra was applied in the "y" direction and offset in the "x" direction by 0.1b as required by NZS 4203: 1992 to provide a torsional effect. The resultant complete quadratic combination (CQC) displacements per floor are given in Table 5.3.

Table 5.3: Summary of Displacements Under Moderate Earthquake Scenario

Floor	Total Displacement mm		Relative Floor Displacement mm	
	X	Y	X	Y
13	127	124	2	3
12	125	121	4	3
11	121	118	5	5
10	116	113	6	7
9	110	106	8	7
8	102	99	8	9
7	94	90	10	9
6	84	81	10	11
5	74	70	12	11
4	62	59	13	13
3	49	46	14	13
2	35	33	15	15
1	20	18	20	18

This analysis indicated a maximum interstorey displacement between ground and level 1 under moderate earthquake shaking of 20mm, and a drift ratio for both levels of 0.0042. The corresponding peak displacement for the NZS 4203 ultimate limit state earthquake is 35mm. As this is associated with a ductility demand of 6, the ductility demand for the “Moderate” earthquake scenario is therefore suggested to be of the order of 3.

These values however need to be rationalised in view of the differences between moderate and large earthquakes that are not taken account of in this spectral analysis. In the absence of more comprehensive time history analyses, the above values are likely to overestimate the actual response as moderate earthquakes are typically weaker in long-period components. They nevertheless indicate that a degree of inelastic action can be anticipated in critical building locations, with larger responses applying to buildings on soft sites where considerable amplification is likely under lesser shaking.

For the purposes of the discussions and qualitative analyses in subsequent sections, representative performance parameters for the critical lower storeys of modern buildings on intermediate soil sites of peak interstorey displacement of 10 to 15mm (drift ratio of 0.002 to 0.003) and local displacement ductility demand of 1.5 to 2 have been assumed.

These values are greater than the peak displacement and ductility demands for a serviceability limit state earthquake of 6mm and 1.25 respectively.

At the above levels of displacement and ductility demand under moderate earthquake shaking, structural damage to primary beam and column members can be anticipated. Appreciable cracking with some spalling of concrete is likely to occur in critical locations such as potential plastic hinge regions.

The degree of permanent displacement is less easy to predict. For the purpose of subsequent post-earthquake scenario comments made in this report, it is assumed that for the set of buildings that are the subject area for this study, permanent displacement is a rare occurrence.

For comparison purposes, it is interesting to note that the HAZUS methodology (***National Institute of Building Sciences***, 1997) prescribes the interstorey drift at the threshold of *slight* and *moderate structural damage* for a high-rise concrete moment resisting frame building as 0.0025 and 0.005 respectively.

The description of *slight* and *moderate structural damage* from the HAZUS User's Manual is:

> **Slight Structural Damage:** Flexural or shear type hairline cracks in some beams and columns near joints or within joints
>
> **Moderate Structural Damage:** Most beams and columns exhibit hairline cracks. In ductile frames some of the frame elements have reached yield capacity indicated by larger flexural cracks and some concrete spalling. Non-ductile frames may exhibit larger shear cracks and spalling.

These parameters and descriptions are broadly consistent with the findings and interpretations of this single-building analysis.

6. Damage Potential of Non-structural and Contents Elements

6.1 General

There is often little engineering control over the selection and installation of non-structural items, as these are often selected by people who were not involved in the building design. Similar comments apply to building contents. Statistical information on the direct cost of repairing non-structural damage is lacking, primarily because normal methods of cost estimating and contracting do not make a distinction between structural and non-structural aspects.

In this section, the nature of damage to the various elements of modern multi-storey buildings resulting from a moderate earthquake are described in qualitative terms. The findings of the previous section in terms of interstorey displacements are used as a point of reference.

Damage potential is discussed under the headings of *non-structural elements* and *contents*.

6.2 Non-structural Elements

The qualitative description of non-structural damage in this section is based on earlier work (***Clark***, 1993) and inspections of fittings, furniture and equipment in a range of buildings. These inspections and assessments to determine appropriate restraints provided an insight into probable failure mechanisms. An appreciation was also gained of the consequential damage that could result from, for example, ceiling mounted equipment breaking loose and damaging desk mounted VDUs, hard drives and the like.

There is a distinct difference between the damage due to *relative* floor displacement (lower floors) and *total* floor displacement (upper floors). Displacement or distortion damage in the lower floors will be in contrast with damage caused by acceleration and velocity in the upper floors. At these upper floors, dislocation of suspended ceilings and ceiling space equipment, and rocking or overturning of equipment, cabinets etc will be the major source of non-structural damage.

Office Levels

(a) Window Glazing

In commercial office buildings, the glazing to the perimeter walls is generally held within an aluminium glazing frame. Each pane of glass is supported on two “settling” rubber blocks, and the four edges of the glass held in rubber gaskets. These gaskets, set in from the edge of the glass within the aluminium frame, provide a weather seal and support the pane back to the frame against face loading. This form of construction allows the frame to move relative to the glass pane in the plane of the glass. Separation between the frame and the edge of the glass is generally sufficient to allow in the order of 20mm inter-storey displacement without damage. Where seismic sub-frames have also been provided, there will be more than sufficient allowance for inter-storey displacement from moderate earthquake shaking. These window frames designed for in plane movement are considered to be “robust” during an earthquake event.

Where damage is likely to occur is in older buildings where there is no separation between the glass pane and the back of the window frame. In other cases, sealant, bedding compound has been used to support the pane. With time, these bedding materials become hard and hence lock the glass into the frame. For this situation the glass is likely to be shattered and would be considered "fragile" in a moderate earthquake.

(b) *Partitions*

Demountable partitions up to 1m in height will have a "robust" performance in a moderate earthquake. The proprietary systems are used to form "workstations" that allow the partitioning to be formed up into modules that are well braced by right angle returns, associated desktops and supporting cabinets.

Framed and lined partition construction is likely to have a "medium" performance in a moderate earthquake. Where the partition is built rigidly between floor and soffit of the slab above, damage is likely to occur at the partition head due to inter-storey displacement. Where the partition is fixed to the underside of the suspended ceiling there is likely to be sufficient flexibility in the ceiling system to allow 20mm of inter-storey without damage. Under face loading, framed and lined partitions should be sufficiently robust to not sustain any significant damage. However, where shelving, storage cabinets or equipment are fixed to the partition they may cause additional loading which cannot be sustained by the partition head to ceiling or slab soffit fixings. Damage is likely to be in the form of fixing failure and damage to immediate finishes.

In the case of glazed partitioning there will be a significant difference between the performance of timber framed as against aluminium framed systems. Where the glass pane is rigidly fitted into the timber frame, performance in a moderate earthquake is likely to be "fragile". In the case of the aluminium frame where the glass pane is supported by rubber gaskets so there is a gap between the edge of the pane and the frame, in-plane movement can take place without damage. For these glazed partition systems their general performance in a moderate earthquake is likely to be "robust".

(c) *Ceiling Systems*

Suspended ceilings can be considered in two groups:

- lightweight tiles,
- heavyweight tiles.

With heavyweight tiles it is possible to have 8 tonnes or more of tiles in any particular office floor. This can give a horizontal loading in the order of 50kN to be resisted by ceiling bracing or the perimeter of the ceiling.

In a moderate earthquake, distortion of the tile supporting grid is likely to occur not only from horizontal forces but vertical wave action induced in the ceiling plane by the building response to the earthquake motion. The combination of effects is likely to cause failure of the grid system connections allowing sections of the suspended ceiling to failure allowing tiles, light fittings and ceiling supported equipment to fall to the floor. Damage can also occur at connections between the suspended ceiling system and partitions that are rigidly fixed to the floor.

When assessing the seismic resistant capability of suspended ceilings, particular note needs to be taken of:

- one or two way grid support system
- grid system connections,
- distribution of bracing over the ceiling plane,
- inhibiting vertical waves forming in the ceiling plane,
- fixing of tiles within the grid system so that diaphragm action can develop between bracing points,
- support of the ceiling system at the ceiling perimeter,
- adequate support of the ceiling grid by the hanger system.

In general suspended ceilings would be considered "medium" in their capability to withstand moderate earthquake shaking.

Light fittings that are "laid-in" to the ceiling grid can cause damage to the grid where the light fitting is significantly heavier than the associated ceiling tiles they replace. The inertia forces of the light fitting can open up the clip joints of the suspended ceiling grid allowing the light fitting to break away from the ceiling system. Any light fitting that falls can damage computer equipment or cause serious personal injury. An additional hazard is the power cabling to the light fitting which is pulled out of the fitting as it falls so that the exposed ends of the wires are left hanging at about shoulder height. Surface mounted light fittings can also be a hazard where the screw fixings are only into the plaster tile or the light mineral fibre tile. These light fittings can also break free and fall to the floor. There is less potential for damage where the screw fixings are taken up through the tile into a timber batten that spans between adjacent grid rails of the suspended ceiling.

(d) Services in Ceiling Space

Services equipment within the ceiling space can consist of:

- air conditioning plant,
- associated ductwork, cabling and pipe runs,
- sprinkler system pipe runs and heads,
- general power and data cabling and pipe runs.

During the 1980's air conditioning was typically provided in commercial buildings by "fan coil" units fitted into the ceiling space to service separate zones within a floor. Air was drawn from the floor zone and either heated with electric coils or cooled by chilled water from a central plant zone. The air was then circulated back into the zone. These individual package units were generally suspended from the soffit of the slab above by four threaded rods. Under horizontal excitation these units could swing freely so that dislocation of their fixings would occur. The weight of the "fan coil" unit would be such as to damage the ceiling and possibly break through. In addition, chilled water lines could be ruptured discharging their contents into the floor space.

Less of a risk but probably more expensive to repair are the condensate drains suspended on light hangers within the ceiling space. These long runs of light plastic piping have a potential to fracture under horizontal motion of the building.

Sprinkler pipe runs may also fracture during horizontal excitation of the building. Damage is likely to occur at screw joints adjacent to a fixed point such as where the pipework passes through a structural wall with long unbraced section of pipework beyond. Relative movement between sprinkler heads and suspended ceilings is also a cause of damage where the sprinkler head impacts on the penetration through the ceiling tile.

Services and data cabling can be damaged where relative movement occurs between plant items, ceiling systems and entry points into the ceiling space. Where cabling has been put in place without providing slack, any movement will put additional strain into the cables that could cause damage. Cabling can also be damaged where it passes through a neat opening between two elements of the building. Relative movement can cause the cabling to be sheared off.

Plant Rooms

(a) Plant and Pipework

There are a large number of cases in earthquakes where plant and pipework are damaged due to the use of relatively light fixings. These light fixings are easily failed under moderate horizontal motion of the building. This is particularly the case where the plant room is located on or at the roof level of the building. At this level increased excitation occurs due to the response of the building to ground motion. Not only can be plant items be damaged due to sliding or overturning but any connecting pipework or cabling can also be affected. This damage can cause disruption down through the building if for example water enters the stair or lift shaft, or flows from floor to floor through services openings. To effect adequate repairs can take considerable time to source appropriate materials and equipment let alone finding the skilled labour in the restoration period to have the work carried out.

Screwed fixings in steel pipe are particularly vulnerable due to the high stress raiser of the threaded joint.

Long runs of water charged pipework are also vulnerable where they are restrained by heavy plant items or pass through concrete elements of the main structure. High inertia forces can be developed in the horizontal direction as the building responds to the earthquake motion.

Relatively minor items of plant can cause damage out of all proportion to their own value. For example storage cabinets located adjacent to a control panel or electronic control equipment can cause complete close down of the control systems if the storage cabinets tips into and damages the electronic equipment.

Damage to control equipment in plant rooms includes both internal damage due to electronic panels being dislodged and damage from heavy items being thrown about inside the cabinets, and from the cabinets themselves sliding or toppling.

Another source of damage is various building parts, materials etc that are often stored in the plant room. These materials can do significant damage if they slide into or fall onto plant or their control systems or connecting pipework and cabling. They can also make access and restoration difficult as they will need to be cleared away before checking and repair can commence.

(b) *Electronic Control Equipment and Cabling*

This equipment is other than that housed in plant rooms such as PABX boards or cabinets, electronic switchboards, UPS systems and sprinkler control equipment. In many cases this equipment is not adequately restrained against horizontal loading and can easily slide, rock and overturn. The most vulnerable equipment are tall data cabinets where individual modem or hard drives are stored in racks. These units as a whole can readily overturn due to horizontal floor motion. UPS systems and stand-by battery racks are very vulnerable due to their high mass and difficulty of attaching directly to a main structural element to take the horizontal inertia forces.

These units are also vulnerable to collateral damage where they are housed in an area likely to be flooded such as a basement below ground. Any discharge of water from a ruptured line or plant item will most probably end up in the basement area. Any sensitive equipment within the basement is very vulnerable to loss during a moderate earthquake. Generally electronic equipment can withstand dousing in clean water for a short period of time. In the case of a flooded basement the water is very dirty with high levels of oil content which results in damage which often requires replacement.

Data and electrical cabling is very vulnerable where it is placed in ducts or vertical risers throughout the building in conjunction with other services. For example the rupturing of a fuel line to boilers in the roof space will cause irreparable damage to associated cabling. As noted previously, cabling that is laid taught with rigid fixings is vulnerable to damage due to differential movement. Electronic equipment and cabling would range from *fragile* to *medium* vulnerability depending on location, inertia mass and stability of the cabinets within which they are housed.

6.3 Contents

General Office

(a) *Storage Cabinets and Shelving*

The contents in open shelving is likely to be thrown out onto the floor which may cause damage to sensitive items as well as obstructing escape paths. Where the cabinet or shelving has a height to width ratio greater than 2.5 then it is likely to rock and overturn if it is not restrained. This overturning has the potential to cause collateral damage to adjacent sensitive equipment. During a moderate earthquake these storage units would be considered “fragile”.

Cabinets with sliding drawers left unlocked or otherwise not secured are subject to overturning as the drawers slide out under horizontal shaking. The sliding drawers themselves present a danger, particularly if the contents are heavy.

Spilt contents also give rise to damage restoration costs either within themselves or where required to be replaced in specific order (eg. catalogued items).

(b) *Electronic Equipment*

Electronic equipment such as VDU's, hard drives, printers, photocopiers and fax machines would be considered "fragile" during moderate earthquake shaking where they are free standing on a desk. Floor mounted equipment is less vulnerable and would be considered in the category of "medium". The duration of strong earthquake motion is critical to the level of damage likely to be sustained. It will require more than one or two pulses to give sufficient movement for the items of equipment to slide sufficiently to come off the edge of the desk. However, they are very vulnerable to damage from failure of the suspended ceiling or the tipping over of tall storage cabinets or shelves.

Cabling is of less of a concern as it is generally loosely laid and of sufficient strength to restrain the equipment from sliding if it comes into full tension.

(c) *Display Stands and Signage*

Display stands can be considered as "fragile" in a moderate earthquake. Not that they are particularly important to the operation of the office or likely to sustain significant damage. However, they are likely to cause collateral damage and obstruct escape paths.

Signage, consisting of boards suspended from ceilings or loosely attached to walls can be a "medium" risk in a moderate earthquake. Where the signage is hung from flexible hangers and the natural period of oscillation of the hanging signage is close to that of the building natural period, resonance can occur. After a small number of cycles of building sway the signage can respond violently causing damage to the ceiling sufficient for it to break away.

For signage attached to walls can also respond violently sufficient to become detached and fall to the floor. This may cause collateral damage or obstruct escape paths.

Kitchens

Kitchens or "tea stations" can also be damaged. Even quite small units within a floor of the building generally have a microwave oven sitting on a elevated bench or wall bracket. These units are considered "fragile" in a moderate earthquake.

Fridges are also vulnerable to rocking and overturning and cooking stoves to moving out from their position. With fridges the major concern is loss of contents whereas for cooking stoves electrical faults can develop if the power cable is damaged due to restraining of the stove sliding motion.

Vulnerability Categories

It is an interesting exercise to review the seismic vulnerability of typical office contents items, both in terms of direct damage potential and subsequent time required for obtaining repairs or replacement. Table 6.1 attributes typical office contents items to the vulnerability categories of *fragile, medium or robust* (refer ***Dowrick and Rhoades*** 1995).

Table 6.1: Typical Office Contents – Summary of Damageable Items

	Item Description	Category	Comments
1.	Computers	Fragile	Restocking time is critical
2.	Photocopiers	Fragile	Restocking time is critical
3.	Facsimiles	Fragile	
4.	TV/ videos	Fragile	
5.	High quality furniture	Medium	Damaged from items falling on surfaces
6.	Filing cabinets	Medium	Some twisted and buckled
7.	Water-damaged files		Sprinkler deluge (where not applicable)
8.	Kitchenware, microwaves	Fragile	Not critical for business

Notes: (i) If effectively seismically restrained, an item should be categorised as *robust*

(ii) All of the above items are insurable

(iii) Water damage to contents is insured against by tenants, and to building fabric, equipment and fittings (eg. carpets) by the owners

6.4 Review of Likely Repair Costs

Table 6.2 on the following page presents a breakdown of the construction costs for a typical multi-storey office building into the principal elements. These figures are extracted from the section on elemental costs of buildings in the *New Zealand Construction Handbook* by ***Rawlinson*** (1997) for a categorisation of *'Office building with air conditioning in the range 6 to 15 storeys'*. The category of 'structural components includes the structural frame, floors (including roof), structural walls and stairs.

Also shown in the table are subjective estimates from the authors of the level of damage in costs terms that such a building may incur in a moderate earthquake, expressed as a percentage of total replacement cost.

The category of *Preliminarie*s includes the following items of relevance to post-earthquake reconstruction:

- Removal and cleaning up of damaged material
- Temporary screens and protection of property
- Authority charges (building consent fees)
- Contractor supervision
- Contingency

Consultants' costs for initially establishing the level of damage, along with subsequent contract administration and verification, are also not included in the above. It is understood that these are typically aggregated separately under the category of the cost of the claims process.

Table 6.2: Breakdown of Construction Costs and Likely Repair Costs For Multi-Storey Buildings Damaged in a Moderate Earthquake

Element	**% Breakdown of Construction Cost**	**Likely Repair Cost Breakdown**
Preliminaries	8%	*1% - 4%*
Foundations	6%	-
Structural components	18%	-
Non - structural components	30%	*5% - 18%*
External walls and glazing	*12%*	*1% - 5%*
Internal walls, partitions and doors	*6%*	*1% - 4%*
Ceilings	*4%*	*1% - 3%*
Other finishes, fittings and fixtures	*8%*	*2% - 6%*
Building services	38%	*1% - 8%*
	100%	***7%-30%***

While the analysis of the case study building in Section 5 identified that some structural damage is likely under moderate earthquake shaking, no repair cost estimate is made alongside structural elements in the table above. This is principally because the level of structural damage and its distribution throughout the building has a high level of uncertainty associated with it, pending further quantitative analysis. Moreover, a major cost contributor to this category can be the extensive opening up of linings and other finishes to ascertain whether or not there is a structural problem.

The exclusion of structural elements from these figures is intended to highlight the potentially significant *additional* impact on the overall likely repair costs ratio if structural repairs are found to be necessary.

Other assumptions inherent in compiling the right-hand column of Table 6.2 include that the exterior glazing system is largely unaffected.

The above breakdown of construction cost differs slightly from that used by ***Hopkins*** (1995) for the analysis for *Wellington After the 'Quake* due to the higher proportional cost of aspects such as building services for modern multi-storey buildings compared to the overall set of buildings.

Damage to services as a result of water saturation from sprinklers is a significant unknown, and has also largely been ignored in these figures.

It should be remembered that the percentages in the right-hand column of Table 6.2 are effectively taken over all levels of a building, whereas a greater variation of non-structural damage with height can be anticipated from moderate earthquake shaking. However offsetting this is the reality that the cost of repairing partially damaged elements *in situ* within a functioning building can exceed the original installation (or full element replacement) cost.

These indicative estimate figures can be compared against established damage ratio parameters. From Table 4.2, the mean damage ratios from ATC 13 for modern medium and high rise frame buildings under MM VIII shaking are 6.2% and 7.5% respectively. The figures from Table 6.2 suggest that these values represent only the lower bound of direct damage that can be anticipated.

7. Anticipated Scenario Following a Moderate Earthquake

7.1 General Scenario

The likely broader community scenario following a moderate earthquake is briefly outlined in this section under the headings of *human response*, *disruption to utility services* and *disruption to access*. This is used to set the scene for consideration of the time implications in terms of restoring normal occupancy in multi-storey CBD premises.

A sample scenario for Wellington based on the specific earthquake scenario developed by McVerry for this project is included in Appendix 2.

Human Response

A moderate earthquake of the nature outlined in the previous sections affecting a metropolitan area would be the biggest in New Zealand since the 1931 Napier earthquake. There would be considerable impact on people in the epicentral region.

In the short term, there would be extensive disruption to everyday activities while the impact of the event is fully assessed, and until basic utility services are restored.

In the medium term, continuing interference with building access would be the biggest disruption for many people. Initially this could result from the isolated badly damaged buildings (eg. unreinforced masonry) impacting (directly or indirectly) on the operation of adjacent buildings. The inspection and repair process for minor structural damage would also prove disruptive for building occupants.

Disruption to Utility Services

- ***Power –*** short-term outages anticipated due to the generally robust nature of generation, transmission and distribution systems. Local interruption may result from the need to isolate some badly damaged buildings.

- ***Telecommunications –*** the generally robust nature of these networks means that limited physical damage should result from this level of shaking. Short-term overload of both landlines and cellular networks is however likely, and overload of cellular systems may continue while relocation of office premises occurs

- ***Water –*** the fracturing of some of the more brittle mains (eg. cast iron, asbestos cement) is likely in areas of soft ground. Structures associated with the collection, treatment and storage of water are unlikely to sustain appreciable damage at this level of shaking. The process of repairing the damaged mains will however involve the shutting down and re-livening of supply to affected areas in the weeks following the event, and this is likely to have a significant disruptive effect.

- ***Gas*** – the extensive use of modern polyethylene piping for reticulation in North Island main centres means that damage and hence significant disruption to supply is not likely in a moderate event. Rupturing of connections into buildings in soft soil areas may however occur due to relative movement.

Disruption to Access

A moderate earthquake would cause considerable immediate disruption to access both from/ to and within the affected city. While damage to transportation networks is not likely to be extensive, there will be a need to systematically inspect bridge structures and the like, and this may limit the non-critical use of those facilities for several days.

Similarly, a number of car parking structures may remain closed for up to weeks while inspections are carried out and minor structural repairs effected.

Construction traffic is likely to have a continuing negative effect on access within an affected city for many months.

7.2 Other Influences on Business Recovery

Other influences on business recovery can be grouped as follows:

Internal

Effectiveness of communications with and access for:

- staff
- key customers
- general customers and the media
- essential stakeholders (suppliers, distributors, insurers, bank, etc)

Ability/ time taken to assess actual impact of earthquake on:

- workplace, equipment and facilities
- financial position
- customers and public (image)
- ongoing business activities

Effective Human Resources strategies:

- flexible management structure
- skill substitution
- welfare and planning to ensure staff availability

External

The availability of (and access to):

- replacement equipment (computer, telecommunications, general)
- telecommunications networks
- service contractors to restore equipment to operational state

In terms of staff availability, it was observed following both the Northridge and Kobe earthquakes that key utility organisations had approximately only 50% of staff turn up in the first 24 hours after the events (***WELG***, 1994 & 1995).

7.3 Summary of the Damage Assessment and Repair Process to be Followed

It is instructive to set down the likely damage assessment and repair process on a step-by-step basis, as follows:

Owner ***(structural and non-structural damage)***	**Tenant** ***(contents damage)***
Loss adjuster to assess damage to structural, non-structural elements (incl. partitions, ceilings, plant & equipment and any water damage)	Loss adjuster to assess damage to contents including water damage
Insurer's engineer to assess above damage and compile repair specification (building consent may be required)	Insurer gives approval for the repair of minor damaged items and the replacement of written-off equipment
Agreement with owner (and owner's engineer) required	Tenant organises repairs, places order for replacement equipment
Contractor prices the repairs	Replacement equipment obtained and installed
Repair work underway	
Repair work completed	
Verification that repair work is to the satisfaction of all parties	

The key difference between *owner* and *tenant* processes is that in the majority of cases, the replacement or repair of tenants' contents will not involve construction contracts. The complications relating to tenant designed and owned fit-outs as highlighted in Section 4 should however be noted.

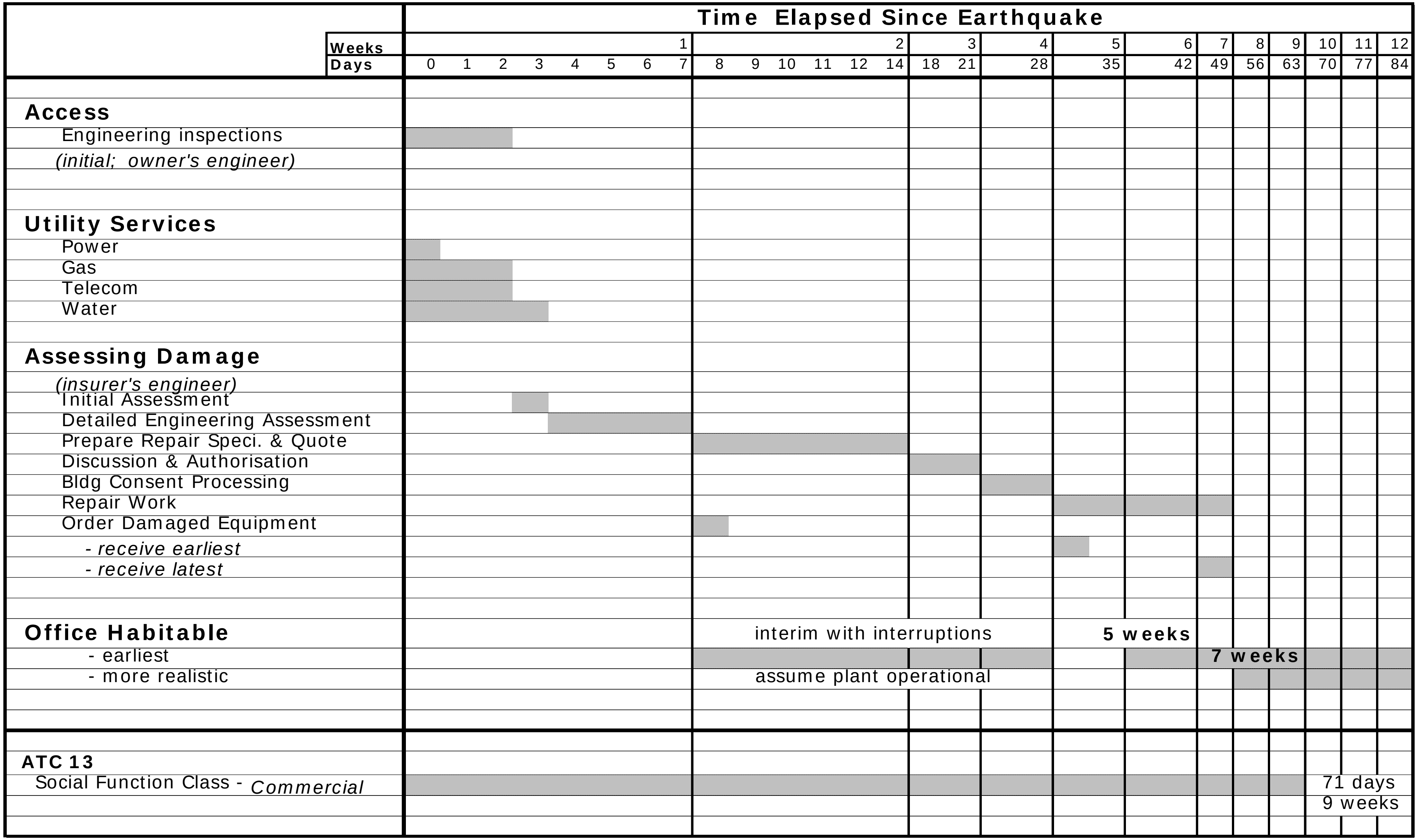
The broader point though is that the ability of tenants to resume normal business operations will be significantly impacted by owner-related activity to investigate and repair structural and non-structural elements.

There are likely to be appreciable difficulties in reaching agreement on the scope of repair specifications for minor/moderate damage. There is a significant cost difference between "*patch repair*" and "*comprehensive or total repair*". This can also have considerable time implications.

A visual representation of this process is shown in the timeline of Figure 7.1. Broad assumptions have been made in order to establish this timeline, which indicates that some multi-storey buildings could take between 5 and 7 weeks before full re-occupancy can be assured. The main question in terms of putting a time-frame to these steps is the availability of suitably experienced adjusters, architects, engineers and contractors.

This first-principles assessment is consistent with the mean value of 9 weeks given in ATC 13 for full usability for buildings in the social function class of *professional, technical and business services* for a moderate damage state.

Fig 7.1: Anticipated Recovery Timeline Following a Moderate Earthquake



8. Conclusions and Recommendations

8.1 Summary of Findings

- A moderate earthquake can be characterised as one that generates MM8 intensity on intermediate soils. In Wellington, such an event is considered to be represented by a magnitude 6.0 to 6.5 earthquake which has a return period of approximately 140 years (probability of occurrence 30% in 50 years).
- The maximum likely interstorey drift of a 13 storey moment resisting frame building designed to NZS 4203:1984 in such an event was found to be 10 to 15mm, and the corresponding local displacement ductility demand between 1.5 and 2. This indicates that a moderate earthquake is likely to cause structural damage to a number of buildings of this type, in addition to extensive non-structural damage.
- The likelihood of structural damage occurring under MM8 shaking contrasts with the qualitative damage descriptions for the lower values of the MM scale, whereby damage is not implied to modern construction until higher levels of shaking.
- Damage ratios that are commonly applied to modern multi-storey buildings for MM8 intensity shaking are around the 6 to 8% level. First principles qualitative assessments based on the above drift levels are used to suggest that ratios of 7 to 30% may be more appropriate. This indicates that typical damage ratios for moderate earthquake intensities represent lower bound damage estimates only.
- Consideration of the insurance and engineering processes for damage assessment and repairs following earthquakes has highlighted that even for buildings sustaining non-structural damage, there are a number of interactive steps involved. These steps can involve owners and tenants with separate but inter-related building, contents and business interruption policies. Analysis of the impact of the likely interaction plus the disruptive effect of repairing non-structural damage has indicated that some multi-storey buildings could take between 5 and 7 weeks before full re-occupancy can be assured.
- An empirical approach for assessing indirect losses for businesses operating in modern multi-storey buildings has been developed. While further development of this methodology is required, it is thought to be of value to tenants in establishing the level of business interruption cover they should have in place.
- An indicative descriptive scenario which emphasises the human reaction to and impact of a moderate earthquake is also included.

8.2 Recommendations

General

- There needs to be a better awareness of the level of damage and disruptive impact of earthquakes that are smaller than "design" events but correspondingly more likely to occur
- The limited protection to non-structural and contents elements in moderate earthquake events afforded by modern ductile frame structures needs to be more clearly conveyed by designers to owners and prospective tenants. This category of construction is essentially untested in terms of actual earthquake exposure in New Zealand.

Specific

- A working party comprising insurance adjusters and earthquake engineers be established to map the claims process for commercial premises following earthquakes, and to identify prior training needs and post-event guidance requirements for the engineering profession and the insurance industry
- Given the extensive use of the MM scale in the analysis and description of historical earthquakes, an improved set of damage descriptors for modern buildings under MM8 and MM9 shaking in terms of both non-structural and structural performance should be developed.
- The findings from this study in terms of structural performance parameters should be further examined with regard to the frequency and duration of shaking from the scenario spectra. This aspect could involve the application of appropriately scaled time history earthquake traces to sample buildings.

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Appendix 1: Outline of a Possible Approach for Assessing Indirect Losses for Multi-storey Buildings

A1 Procedure for Estimating Interruption Losses

A procedure for estimating losses due to the interruption of occupancy following an earthquake is summarised in Table A.1 following.

The four required input parameters for this procedure are:

- Lettable area
- Unit rental
- Weekly turnover (gross income)

  (based on an estimate of the ratio $\frac{\textit{rental cost}}{\textit{gross income}}$)
- Post-earthquake down time

The objective of the methodology is to be able to make a broad estimate without needing to obtain detailed commercial information.

As the example for the case study building outlined in Table A.2 illustrates, a general estimate of the indirect loss caused by an earthquake can readily be obtained with the use of the default parameters.

While the result provides a broad estimate only, it is believed that the order of magnitude of the result is reasonable. Such a rapidly obtainable number is of both general interest and specific application.

It should be noted that this methodology can be applied equally to earthquakes of greater magnitude.

A2 Categorisation of Tenancies in Multi-storey Buildings

In order to identify the vulnerability to earthquake of different tenancies in multi-storey buildings, a basis for categorisation is required.

The following five key qualitative and quantitative parameters are considered to provide a broad basis for such a categorisation:

(1) **Size of Tenancy** (area - *m2*)

(2) **Location of Tenancy**

- CBD core }
- CBD outer } (rental - *$/ m2*)
- non-CBD }

(3) Activity/ Function/ Operation

- commercial high occupancy }
- commercial low occupancy } (occupant density - *persons/ m2*)
- retail }

(4) Vulnerability to Moderate Earthquake

- unrestrained computers/ electrical/ telecommunications equipment (*computers etc/ m2)*

(5) Maximum Sustainable Downtime

(eg. number of working weeks before business at risk of failure)

An analysis of the case study building investigated as a part of this project indicated that there is a considerable range of occupant and computer densities.

Table A1: Procedure for Estimating Interruption Losses From Office Rental

Input/Step	Element	Value	Definition	Default Value
Input 1	Lettable Area	A		
Input 2	Unit Rental	B		
Calculation Step 1	Annual Total Rental	C (=AxB)		
Calculation Step 2	Gross Income	D (=CxOCF)	OCF = Occupancy Cost Factor	(i.e. rent = 5% of gross income)
Calculation Step 3	Weekly Turnover	E (= D/52)		
Calculation Step 4	Interruption Loss	F (= ExADT)	ADT = Average Down Time Post-earthquake	10 weeks

***Assumptions*: (1)** All operational overheads are incurred during the post-earthquake down time. This is conservative, as expenses such as power, stationery purchases, etc will not be incurred during this time.

(2) The *Average Down Time Post-Earthquake* assumes that there is no business continuance plan in place, as in many cases attempts would be made to set up alternative or interim operations in order to reduce this period. There are however higher costs associated with such endeavours.

(3) The *Interruption Loss* estimates relate to actual losses only, and not to costs associated with recovering market share (cross-refer to Assumption (2)).

Table A2: Worked Example For Case Study Building

Element	Value	Comment
Lettable Area	300 m^2	
Unit Rental	$250 $/m^2$	
Annual Total Rental	$75,000 $/ year	
Gross Income	$1,500,000	Default value OCF = 20 used
Weekly Turnover	$28,846	
Interruption Loss	**$288,462**	Default value ADT = 10 weeks used

Appendix 2: Scenario: A Significant Earthquake Affecting Wellington

Scenario & Context

An earthquake of magnitude 6.3 strikes Wellington at 2pm on a weekday. This earthquake is centred 40km from central Wellington, with a depth of 10 to 30km, and gives rise to 10 to 15 seconds of strong shaking.

The felt intensity of this event is Modified Mercalli 8 on alluvial soils (greater on soft sediments).

This is not the "big one", but a strong and damaging earthquake nevertheless - the like of which has not been experienced in a major urban area since the 1931 Napier event. The probability of such an event is approximately 30% in 50 years (140 year return period).

Human Effects & Response

- a number of deaths (*est. 50*) and some serious injuries (*est. 250*); people trapped in buildings (*est. 80*)
- people are milling around in the streets of CBD uncertain of what they should be doing

Summary of Building Damage Characteristics

Overview

- ♦ a number of unstrengthened unreinforced masonry buildings collapsed (*eg. Cuba St, Courtenay Pl)*
- ♦ a small number of early concrete multistorey buildings (WCC Classifications B & C) collapsed (*especially those on the seaward side of the pre-1855 beach eg. Featherston St, Thorndon Quay)*
- ♦ some brick parapets, concrete panels and glazing sections have fallen into streets
- ♦ modern multi-storey buildings sway appreciably with signs of non-structural cracking evident (and in some cases, structural distress); lifts stopped
- ♦ unrestrained computer equipment, heavy furniture and shelving in offices toppled; ceiling tiles fallen; some doors jammed

General Performance Profile

- ♦ Few buildings have ***collapsed*** *(some partially collapsed)*
- ♦ A number of buildings have sustained ***structural damage***
- ♦ Many have received considerable ***non-structural damage***
- ♦ Some have ***little damage***

Modern Quality CBD Property Portfolio

- A few have sustained ***structural damage***
- Most have received ***non-structural damage***
- Some have ***little damage***.

Post-earthquake Issues From a Building Management Perspective

- Engineers will be needed:
  - *to confirm immediate safety and occupiability of damaged buildings*
  - *to carry out detailed investigations and prepare repair specifications*
- Building contractors will be needed, particularly for key trades such as fixed partitioning, ceilings and glazing
- Even if buildings have not received structural damage, disruptions will be due to:
  - *damaged adjacent buildings*
  - *disrupted utility services* (*unreliable water supply, overloaded telecommunications)*
  - *engineering investigations to check whether there has been structural damage*
  - *the messiness of the repair/ replacement process for linings, ceilings, etc*

Event timeline *(indicative only)*

0 to 2 hours

- chaos generally; most people will not want to re-enter the buildings they were in for fear of aftershocks, and so will have nowhere to go
- people will be trying to make contact with family members, and those with cellphones will quickly find an overload situation
- Newstalk ZB will be trying to gather and convey the extent of the problems (*but few in the city streets will have transistors with them*)
- State of Emergency declared

2 to 6 hours

- people will be wanting to head home. Transport agencies will be trying to establish what systems and routes are operative (*there will have been some slippage and road damage, but not necessarily widespread*), and will be working closely with Emergency Management agencies
- householders (*owners and tenants*) will be wanting to know if their houses/ buildings are safe to occupy, and what utility services they are likely to have for the approaching night (*power is being restored, water supply is affected in some areas, telecommunications are overloaded with only some messages getting through*)

6 to 24 hours - the full citywide and regional impact of the event will be becoming established
- people will be wanting to know about the extent to which the City will be functioning the next day
- power and telecommunications restored to most areas with ongoing disruption; water supply intermittent in many areas depending on location
- people will be looking to councils and emergency services for quick feedback on the safety status of their buildings

24 to 48 hours **- utility services being restored (*basic service only*)**
- threat of major aftershocks diminishing
- **insurance assessment process underway for houses and offices**
- badly damaged buildings are being hoarded up/ some streets may be cordoned off
- **businesses desperate for access**, and clamouring at Council (*remember, this is not the big one, and many buildings are unaffected - what form of "sign-off" will Wellington City Council require from owners that their buildings <u>are</u> safe?)*
- power to damaged/ cordoned off buildings is off, and so health issues regarding food are developing

At 1 week **- damage assessment (*engineers and insurance agents*) in full swing, along with repair work**.
- the desperation of businesses for access continues, with access limitations due to safety being a real problem (*eg. is it safe to be in a building (largely undamaged) which is next to a damaged building; is it safe to work in a building where minor structural and significant non-structural repairs are being carried out?)*
- Council is under real pressure to approve structural repair work - questions relating to older buildings will arise, such as the applicable structural standards for repairs/ reinstatement and the extent of upgrade of fire safety that Council should require?
- a high level of "social confusion" exists - people in damaged houses are realising that they cannot re-inhabit them for longer than they thought
- what immediate action should be taken for damaged heritage buildings?

At 1 month - the same issues as for at 1 week above, but increasingly driven by a desire to get back to normal
- "social confusion" diminished, as people are more fully acquainted with what the event means for them
- instances of previously "hidden" damage will be being uncovered
- the repair "process' will be taking much longer than most people anticipate due to the insurance "chain" and the need in many cases for people to obtain second opinions
- Council will be under real pressure in terms of consent processing