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Preparation of Comprehensive Earthquake Hazard Maps

Report on Mapping Methodology

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1. INTRODUCTION

As part of a strategy that Wellington Regional Council is currently developing on earthquake and geological hazards, we have prepared a series of relative seismic hazard maps for the region.

The project was completed in five main stages:

- review of relevant literature on the preparation and nature of comprehensive or multi-factor hazard maps
- review of existing and potential user needs with respect to the nature and presentation of earthquake hazard information in a comprehensive hazard map format
- development of concepts/options for presenting the hazard information and general map design
- development of methodology to combine the various earthquake hazard components into a single map
- printing of multiple copies of each comprehensive earthquake hazard map.

The aim of the project was to produce technically sound, defensible, and innovative earthquake hazard maps for the five main urban parts of the Wellington region; Wellington, Porirua, Lower Hutt, Upper Hutt, and Kapiti. The various earthquake hazard components have been combined and presented in a single map for each area. The maps are expected to satisfy the requirements of a range of existing and potential users of earthquake hazard information.

This project follows from previous projects that have produced reports and maps showing the hazard due to ground shaking, liquefaction, slope failure, fault displacement, and tsunami inundation. One of the outputs from each of these projects is a digital map for each hazard, in Arc-Info format. These digital data have provided the information base for preparation of a combined hazard map.

Because the base data are in Arc-Info format, we have been able to use geographic information system (GIS) processing to manipulate, combine and display the hazard information.

2. INDIVIDUAL HAZARD STUDIES

2.1 Earthquake scenarios

The individual hazard studies were based on two earthquake scenarios, except for the tsunami inundation hazard study which used four fault displacement scenarios.

Scenario 1 is for a large, distant, shallow earthquake that produces MM V-VI shaking intensities in bedrock over the Wellington area. The return period of this event is 20 to 80 years. The Scenario 2 earthquake is centred on the Wellington - Hutt Valley segment of the Wellington Fault, and associated with a magnitude 7.5 earthquake at a depth less than 30 km. The mean recurrence interval for such an event is about 600 years.

For the slope failure hazard study an intermediate scenario was introduced, with shaking levels between the Scenario 1 and 2 earthquakes, and return period also intermediate between the Scenario 1 and 2 events.

The mapped tsunami hazard was based on further movement of the West Wairarapa Fault, which has up to 30% probability of displacement in the next 100 years.

2.2 Ground shaking

The project on ground shaking carried out in 1991 derived the shaking response of five ground shaking hazard zones for the two earthquake scenarios. The five zones were determined according to the nature and thickness of geological deposits.

For each zone, and for each scenario, a suite of ground motion parameters were predicted. These included expected Modified Mercalli intensity (MM); peak horizontal ground acceleration (pga); duration of strong shaking; and amplification of ground motion with respect to bedrock.

The ground motion parameters associated with the five zones are given in Table 1

description	polygon attribute	scenario 1		scenario 2	
		MM	pga	MM	pga
least shaking	1	V-VI	.04g	IX	.65g
	2	VI	.06g	IX-X	.65g
	3	VI-VII	.06g	IX-X	.65g
	4	VI-VII	.06g	IX-X	.65g
greatest shaking	5	VIII-IX	.15g	X-XI	.70g

Table 1. Ground shaking polygon attributes from Arc-Info.

A significant point about the ground shaking maps is that they show ground response for only two earthquake scenarios. The overall ground shaking hazard in the region is made up of shaking caused by many earthquake scenarios. This needs to be recognised and taken into account when preparing the combined earthquake hazard maps.

2.3 Liquefaction

The hazard information on liquefaction identifies areas where liquefaction may occur if ground shaking is severe enough. This hazard is closely linked to the ground shaking hazard, and the probability of liquefaction occurring depends on the frequency and strength of shaking. It may be thought of as compounding the effects of ground shaking.

Some judgement is required in assessing the effects of this hazard since the areas indicated are zones of potential liquefaction. The extent of actual liquefaction in a given earthquake will depend, not only on the level of ground shaking, but more critically on the nature of the underlying soils and groundwater conditions at the time of the earthquake. The maps do not claim to have determined the nature of soils at every site, but rather identify locations where the potential exists for liquefaction.

The Arc-Info database contains polygons showing areas with potential for liquefaction, and another set of polygons showing areas with varying ground damage potential (due to liquefaction of underlying soils). For the purposes of hazard combination, we have used the liquefaction potential data which consists of five zones.

The likelihood of liquefaction for each of the five zones is given in Table 2.

description	polygon attribute	scenario 1	scenario 2
high	1	yes	yes
moderate	2	unlikely	likely
low	3	not likely	maybe
variable	4	possible	possible
no hazard	9	no	no

Table 2. Liquefaction polygon attributes from Arc-Info.

2.4 Slope failure

The hazard of earthquake induced slope failure was based on knowledge of the geological materials, slope attitudes, and relationship to past slope failures. The various factors contributing to slope failure were combined to produce five zones of different slope failure potential, ranging from very low hazard, to very high.

As with the ground shaking hazard information, the slope failure hazard data does not provide an overall measure of the effects of slope failure hazard over a period of time. There was an intermediate scenario considered which provides some further information in this respect.

The slope failure effects associated with data in the Arc-Info database are given in Table 3.

description	polygon attribute	scenario 1	scenario 2
very low	5	very minor	minor
low	4	very minor	significant
moderate	3	very minor	severe
high	2	minor	very severe
very high	1	significant	very severe

Table 3. Slope failure polygon attributes from Arc-Info.

2.5 Fault displacement

The hazard from ground rupture during an earthquake with associated fault displacement is shown on a series of maps. The maps show the fault surface location, where known, and give background information on the characteristics of each fault. The maps do not indicate the likely extent of the ground rupture zone.

The Wellington Regional Council Arc-Info database contains a series of lines showing the location of surface traces of active faults. For the purposes of this study, we have generated a corresponding polygon around each fault which is 20 m on either side of the mapped fault trace.

The fault hazard data are given in Table 4.

description	polygon attribute	scenario 1	scenario 2
in fault zone	1	no effect	displacement
out of fault zone	0	no effect	no effect

Table 4. Active fault displacement polygon attributes.

2.6 Tsunami inundation

The tsunami hazard has been reported for Wellington Harbour only, so is not taken into account for the Porirua and Kapiti maps. The hazard is determined from a map showing areas that will be inundated during the scenario event, so the Arc-Info database is simple; parts of the Wellington and Hutt map areas will be inundated, or they will not.

There are no data on the gradation of tsunami effects within the inundated area, although it is reasonable to assume that these will be proportional to the depth of inundation, although not necessarily in a linear manner.

3. HAZARD COMBINATION PROCEDURES

The earthquake hazards that affect the Wellington region are of varying type, frequency, and effect. If the hazards are to be combined in a meaningful way, they must be combined so as to fairly show and compare these effects over a period of time.

How does one compare tsunami hazard with that of slope failure or of ground rupture? They produce quite different effects and occur at different time intervals. Ground shaking under one scenario will produce certain assessed effects. But is it reasonable to simply compare these effects with that of fault displacement when the fault rupture takes place at a different location and with a different assessed return period? The ground shaking scenario represents but one of a number which could occur over the same period.

A further point to be considered is the influence of the distribution of built infrastructure on the assessed effects. Clearly, if no assets are built in fault zones, then there will be no risk due to fault displacement. However the hazard does exist. It is important that a combined earthquake hazard map clearly show the relative level of hazard throughout the region that is unrelated to the development of the land at the present time.

From our review of the literature, it appears that previous attempts at combining earthquake hazards have involved relatively simple addition of an attribute that is common to each hazard. The group at Stanford University (King et al 1994) added expected damage factors for each hazard, while the Oregon Department of Geology and Mineral Industries (Mabey et al 1995) manipulated in an additive way subjective factors associated with the individual hazards.

We believe that it would be more meaningful to take account of the various effects of each hazard, and the relative probabilities of occurrence. The effects of each hazard can be normalised by assessing the value of damage to a typical unit of infrastructure, assuming that the unit of infrastructure is the same across the region. The effects of each hazard in turn are then assessed for each location, and then combined taking account of the relative probability of each hazard occurring.

4. METHODOLOGY FOR HAZARD COMBINATION

The main steps in our methodology were:

a. Assume a range of infrastructure is at risk, uniformly distributed over the region.

b. Establish damage ratio relationships for each element of infrastructure, for each hazard.

c. For each grid position on the map, determine the severity of each hazard.

d. For each grid position, for each hazard, compute the damage amount for each facility type.

e. Compute normalising factors for each hazard to take account of relative probability, and of cumulative effects.

f. For each grid position, sum the normalised damage amounts for all hazards.

g. Plot the sum of normalised damage amounts for all grid positions in a way which allows ready appreciation of the range and variation of damage amounts.

5. DETAILED METHODOLOGY

5.1 Representative assets at risk

Different types of asset are affected in different ways by each of the individual earthquake hazards. To determine a representative unit of infrastructure that can be used for this project, the analysis of Wellington's infrastructure presented by Hopkins (1995) has been used. In the 1995 study, assets in various categories and areas were listed to determine the total replacement value of the built environment in the Wellington region.

The asset values presented by Hopkins (1995) have been reallocated into eight groups (Table 6). The groups have been assigned to reflect differences in response to the earthquake hazards.

For this study we are concerned with the percentage split of the total assets into each group, so that we can then use this as a weighting for the effects of the various hazards. Many more categories could have been identified, but we believe that these eight groups are adequate for the purposes of combining the hazard effects.

We need to make the assumption that this percentage split of total assets exists at all points in the region. When we work with a grid based GIS structure, then each square of the grid is assumed to have assets in the proportion shown in Table 6, and to the same total value.

5.2 Damage ratio relationships

To enable a comparison of hazard effects, we propose to calculate the damage to each of the eight asset categories for each of the earthquake hazards. Where accepted damage relationships are known, we have adopted these. Where data are lacking, we have made our own assessments by considering the nature of the hazard and the assets that are affected.

Because we are using the damage ratio relationships in a relative way, it is not important that we have absolute precision in these relationships.

Tables 6 - 10 give the damage ratios we have used for this project.

Damage ratio data for ground shaking is generally better documented than for any of the other hazards. The ratios proposed for this project have been determined by judgement based on ATC-13 (Applied Technology Council, 1985).

	bldgs	roading	bridging	rail	airport	port	water	sewer	storm	gas	elec	Telecom	broadcst	total	% of total
Categories of Infrastructure															
Surface Infrastructure	0	1200	350	1500	40	100	60	20	40	30	20	10	10	3380	**6**
Retaining Structures	0	300	70	400	20	100	60	10	30	20	30	30	10	1080	**3**
Underground Services	0	100		400	10	20	600	600	330	400	300	500	30	3290	**8**
Overhead Services	0	20		400			0				600	10	10	1040	**3**
High Rise	7000												70	7070	**15**
Medium Rise - piled	9000					150	20					40		9210	**20**
Med-Low Rise - not piled	8000				30	30	40	30	10	10	550	30	20	8750	**20**
Residential	13000						0							13000	**25**
Total($M)	36707	1622	426	2670	103	402	780	660	406	467	1501	622	150	46516	**100**

Table 5. Split of infrastructure assets in the Wellington Region.

	% Damage					
	MM7	**MM8**	**MM9**	**MM10**	**MM11**	**MM12**
Categories of Infrastructure						
Surface Infrastructure	0.0	0.0	3	6	12	30
Retaining Structures	0.0	5	10	20	40	80
Underground Services	0.0	0.0	3	6	12	24
High Rise	0.0	3	7	15	30	60
Medium Rise - piled	0.0	2	5	10	20	35
Med-Low Rise - not piled	0.0	2	5	10	20	40
Residential	0.0	2	5	10	20	50
Overhead Services	0.0	0.0	1	3	10	30

Table 6. Ground shaking hazard damage ratios.

	% Damage					
	MM7	**MM8**	**MM9**	**MM10**	**MM11**	**MM12**
Categories of Infrastructure						
Surface Infrastructure	0.0	0	2	7	15	15
Retaining Structures	0.0	0	2	20	20	20
Underground Services	0.0	0	1	12	12	12
High Rise	0.0	0	0	0	0	0
Medium Rise - piled	0.0	0	0	0	0	0
Med-Low Rise - not piled	0.0	0	3	20	20	20
Residential	0.0	0	1	7	10	15
Overhead Services	0.0	0	0	2	5	8

Table 7. Liquefaction hazard damage ratios.

	% Damage				
	Very Minor	**Minor**	**Significant**	**Severe**	**Very Severe**
Categories of Infrastructure					
Surface Infrastructure	5	s	30	70	120
Retaining Structures	5	10	30	70	120
Underground Services	0.0	5	20	50	80
High Rise	0.0	10	20	50	120
Medium Rise - piled	0.0	10	20	45	100
Med-Low Rise - not piled	5	10	30	70	120
Residential	5	10	30	70	120
Overhead Services	0.0	5	15	30	60

Table 8. Slope failure hazard damage ratios.

For liquefaction damage ratios, we have assessed the damage additional to shaking that is expected when liquefaction occurs. The damage ratios also reflect the threshold level after which liquefaction is possible, and the understanding that there is little increase in damage due to liquefaction at stronger levels of ground shaking.

Slope failure damage ratios were derived for this project, and are intended to reflect both the susceptibility and the scale of slope failure effects.

	damage
	%
Categories of Infrastructure	
Surface Infrastructure	30
Retaining Structures	10
Underground Services	30
High Rise	5
Medium Rise - piled	10
Med-Low Rise - not piled	20
Residential	15
Overhead Services	5

Table 9. Tsunami hazard damage ratios.

	damage
	%
Categories of Infrastructure	
Surface Infrastructure	100
Retaining Structures	100
Underground Services	80
High Rise	80
Medium Rise - piled	70
Med-Low Rise - not piled	80
Residential	60
Overhead Services	60

Table 10. Fault hazard damage ratios.

Fault rupture damage ratios we assessed to reflect damage only in the 20 m wide zone on either side of the mapped active fault trace.

Our assessment of tsunami damage ratios are also original assessments, and apply to the average condition in the zone of inundation. Effects would be more severe closer to the harbour, and less severe towards the inner edge of the zone. It could be possible to derive a GIS procedure that would provide a more realistic distribution of effects.

5.3 Probability and cumulative effect factors

The Wellington Regional Council maps and supporting digital hazard data are generally for two earthquake scenarios. The damage ratios we have proposed are based on the assumption that the scenario occurs. However there is no consideration for the relative probabilities of the scenarios. Also, there is no account taken of the cumulative effects of tsunami, ground shaking, slope failure, and liquefaction hazard occurring over a period of time.

To account for the time effects of different scenarios when deriving a combined hazard map, we propose to apply two factors to the computed damage effects. These are a probability factor (PF) and a cumulative effects factor (CF) which are assessed for each hazard type. These factors have been normalised against the Wellington Fault event scenario, which has an average return period of 600 years.

A summary of the factors used is given in Table 11.

Hazard	Probability Factor (PF)	Cumulative Factor (CF)
Tsunami	0.71	2.00
Fault Movement		
Wellington Fault	1.00	NA
Wairau Fault	0.83	NA
Pukerua Fault	0.09	NA
Ohariu Fault(Kahao)	0.36	NA
Ohariu Fault(Porirua)	0.18	NA
Wairarapa Fault	0.71	NA
Slope Failure	1.00	2.00
Ground Shaking	1.00	3
Liquefaction	1.00	3

Table 11. Probability and cumulative effects factors.

The tsunami hazard data estimate the inundation from one event, that of a large earthquake with displacement of the West Wairarapa Fault. The report on which the hazard data are based (Gilmour and Stanton, 1990) shows that tsunami effects could occur on a number of other occasions. A large earthquake with ground surface displacement on the West Wairarapa Fault has a recurrence interval of 1000 years. Assuming that a Poisson distribution applies, we can calculate a probability factor (PF) to normalise the probability of this event occurring relative to our base case event, the Wellington Fault earthquake (scenario 2).

$$1\text{-}e^{T1/600}$$
$$1\text{-}e^{T2/600}$$

where T1 = recurrence interval of Wellington Fault (600 years)
T2 = recurrence interval of west Wairarapa Fault (1000 years)

In this case, PF of tsunami inundation is 0.7. It is less likely to happen than scenario 2, and we need to weight our combined hazard calculations accordingly.

The cumulative effect of all other possible tsunami generating earthquakes also needs to be considered. Gilmour and Stanton (1990) presents a table of events and

indicates the relative extent of inundation for each. From their data, we have assessed a cumulative effect factor (CF) of 1.5. This means that the overall effect of tsunami over a 600 year period can be expected to be more than that of the scenario event used in the 1990 study.

With fault displacement, the cumulative factor is not applicable since none of the mapped active faults are expected to experience more than one displacement event in the normalising period (600 years).

The cumulative effects of ground shaking are significant, since there are many other earthquake sources that will cause ground shaking in the Wellington Region besides the two scenario events. Smith and Berryman (1990) presented a table of average times between a range of MM intensities in the Wellington Region (Table 12). The cumulative effect of these intensities occurring over a period of time is not only a function of the probability of the intensities occurring, but also of the damage each causes. Thus damage ratios, or at least the shape of the damage ratio curve against MM intensity, will contribute to the cumulative effect. We have estimated the cumulative effects factor for ground shaking by taking a typical shape of a damage ratio curve, and using it to compute the sum of the products of probability and damage for the Wellington Fault event (scenario 2). We have done the same considering the long term situation with shaking hazard due to all earthquake sources. By comparing the two calculations, we have a measure of cumulative factor that we need to apply to the Wellington Fault event scenario.

MM intensity		**average time (years) between occurrences of intensity in the Wellington Region**			
at typical site	**at hard rock site**	**from intensity data**	**from all faults**	**from Wairarapa subduction thrust**	**Wellington City Wairarapa + thrust + Wellington Fault**
6 or greater	5	7 (±1.5)			
7 or greater	6	19 (±7)			
8 or greater	7	75 (±53)			
9 or greater	8	150 (±150)	150-180 (140-200)		
10 or greater	9	380 (±380)		330-500	210-270

Table 12. Return times for ground shaking, after Smith and Berryman 1990.

To determine an appropriate cumulative factor for liquefaction, similar calculations have been made as for ground shaking. The variation of damage ratio with MM intensity is taken into account, and in particular, we have attempted to reflect the onset of liquefaction at high MM levels, and the flattening off of the additional effects at higher MM values.

6. IMPLEMENTATION OF METHODOLOGY USING GIS

To manage the calculation process and the production of map outputs, we have utilised our in-house GIS system (TECHBASE). The WRC Arc-Info data has been translated from shape files into the appropriate TECHBASE relational database structures.

We have then constructed a 2-D database table (cell table, with 10m grids) that covers each map area. At the centroid of each cell, we have assigned the relevant Arc-Info polygon attributes to a field corresponding to each hazard polygon. We were then able to carry out calculations between each of these fields on a record by record (or grid centroid) basis.

The calculations then followed for each hazard:

- calculate the damage for each item of infrastructure for each hazard, based on the damage ratios given in Tables 6 through 10.
- modify the liquefaction damage based on an assessed likelihood that liquefaction will occur in the area
- total the damage for each hazard
- add the damage for each hazard at each cell centroid to get the total damage due to combinations of hazard, a combined hazard index (CHI).

To display this information, ie the variation in CHI, we have adopted a gradational colour scale ranging from cold colours for low hazard (blues) to hot colours for high hazard (reds). The colour scale used is the same across all four maps, so that meaningful comparisons can be made of the combined earthquake hazard across the maps.

The maps for each area also have a table of information that indicates appropriate mitigation measures.

7. CONCLUSION

The methodology we have proposed fulfils the requirements of the project brief. The effects of the various hazards have been normalised so that they can be directly compared. This has been done by assuming that there is a uniform distribution of assets throughout the region, and by considering the effect of the earthquake hazards on these assets by using appropriate damage ratios.

The combined hazard maps will represent the relative severity of the combined effects of the hazards on the region. Our approach is meaningful, in that the cumulative hazard index is directly related to potential damage to assets. It is useful because it provides anyone contemplating the building of new assets with an overview of relative risk.

Because the maps are plotted from digital data, it is possible to make more specific maps of relative earthquake effects, either for any selected combination of hazards, or selection of asset types.

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