EARTHQUAKE GROUND DAMAGE HAZARD STUDIES AND THEIR USE IN RISK MANAGEMENT, IN THE WELLINGTON REGION, NEW ZEALAND

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SUMMARY

Earthquake ground damage hazards pose a significant risk to infrastructure, lifelines, buildings and life in urban areas. Lifelines such as transportation, energy, water, wastewater and communications networks are important for the survival of the community in the aftermath of earthquakes. Hazard identification, awareness, vulnerability and risk assessment, mitigation and preparedness are important to be able to reduce the risk from earthquakes.

The paper illustrates the assessment of ground damage hazards such as liquefaction and slope failure, and mapping with the aid of geographical information systems, through studies carried out in the Wellington Region of New Zealand. The methods developed and used for the ground damage hazard studies are outlined. The hazard maps have been used to consider the effects of earthquakes on lifelines, commercial and residential development and infrastructure, and the associated risk.

The use of the hazard maps in developing processes and criteria aimed at reducing the risk to development is outlined through appropriate examples. Assessment of the risk to lifelines such as water supply, telecommunication and road networks helps manage the risk, through prioritisation and mitigation or planning for emergency preparedness. Risk-economic assessments can be a valuable tool in this process.

INTRODUCTION

New Zealand lies along the Pacific Rim and has a high level of earthquake hazard. New Zealand's capital, Wellington, has a high risk from earthquakes due to a combination of high seismicity, unfavourable terrain and concentrated development. Over the past decade, there has been significant effort in New Zealand to study and quantify the impact of earthquakes on the community, infrastructure and lifelines. Given the high risks, much of this work was initiated in Wellington.

In New Zealand, the Resource Management Act 1991 places a responsibility on local authorities for "the control of any actual or potential effects of the use, development or protection of land, including for the purpose of the avoidance or mitigation of natural hazards …". The Act has encouraged local authorities to take a more active role in helping the community to become prepared for natural hazards such as earthquakes. Local authorities are developing strategies to deal with natural hazards. The Wellington Regional Council has been the first in New Zealand to recognise the importance of earthquake hazard mitigation, and has an objective that "Any adverse effects of natural hazards on the environment of the Wellington Region are reduced to an acceptable level" (Wellington Regional Council, 1995). This will need to be a long term and ongoing objective given the high earthquake hazards in the Wellington Region.

A number of studies to assess the earthquake hazards were commissioned by the Council to identify and present the hazards in the region, and included earthquake ground damage hazard studies and risk studies which are

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outlined in this paper. These have been complemented by studies by the Wellington Earthquake Lifelines Group, which has considered the risk to lifelines on a very broad scale, and helped increase the awareness of the

risk from earthquakes. A number of follow-on studies have been initiated by territorial and lifeline authorities to assess the risk to specific infrastructure and lifelines. Some of these studies have included prioritisation and consideration of mitigation measures to help with risk management.

HAZARD IDENTIFICATION STUDIES

Earthquake Hazards

Earthquakes are commonly associated with some or all of the following hazards leading to an impact on the people, built and natural environments :

- Fault rupture
- Ground shaking
- Ground liquefaction
- Slope failure
- Tsunami and seiche

Fault rupture hazard studies for the Wellington Region were carried out by the Institute of Geological and Nuclear Sciences based on the available information on active faults supplemented by field studies. This led to the publication of fault rupture hazard maps. Ongoing studies are leading to further refinement of this information. Figure 1 shows the main active faults in the Wellington Region.

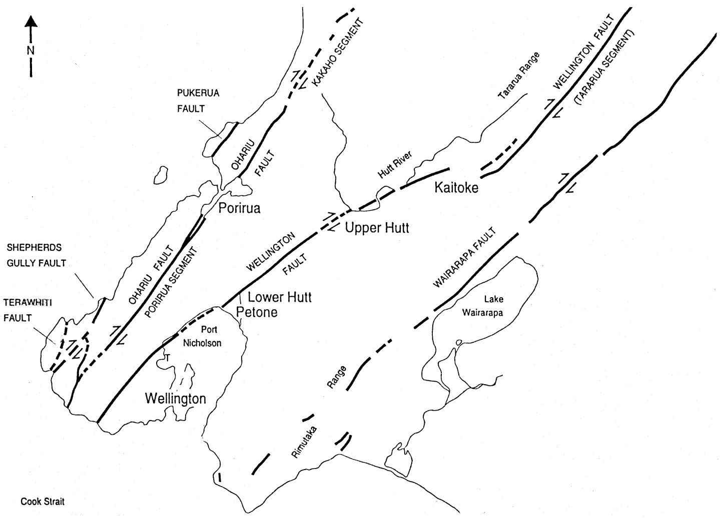

Figure 1 : Active Faults in the Wellington Region

A study to assess the ground shaking and its geographical variation across the region was carried out by the Institute of Geological and Nuclear Sciences for the Wellington Regional Council. The studies considered the known active faults and their return periods for earthquake events, the surface geology, and the characteristics of sediments and microzone effects monitored by instruments in different areas. Ground shaking hazard maps were prepared and these reflected the likely level of amplification of shaking across the region.

A study of tsunami hazards led to a map showing the areas in Wellington City likely to be inundated by tsunami (Gilmour and Stanton, 1990). The study indicated that the worst tsunami run-up heights, estimated to be up to 4.8 m, would come from rupture of the Wellington Fault, which can cause a magnitude 8 earthquake. The southern coast of the Wellington Region could experience a sudden onrush of water. Inside the harbour it is likely to be more in the form of flooding, and this could lead to inundation of much of the Wellington Central Business District.

The study of liquefaction and slope failure hazards is discussed below in more detail.

Liquefaction Hazards

Opus International Consultants assessed and mapped the liquefaction hazards in the urban areas of the Wellington Region. The Wellington Regional Council commissioned the study and published the maps. A specific methodology was developed for the liquefaction hazard study, and is described by Brabhaharan et al (1994). The assessment was based on :

- A review of historical records of liquefaction in the region compiled from published literature, newspaper and archive records.

- Accessible information compiled from past site investigations in the region, and supplementary information from specific site investigations to fill critical gaps in the data.

- Two earthquake scenarios – a magnitude 7.5 earthquake on the major active Wellington Fault which runs through the urban areas of the region, and a distant magnitude 7 earthquake (some 100 km away) which would give low accelerations on bedrock, but with potential for significant amplification on deep/ soft sediments. The ground shaking maps and peak ground acceleration estimates, which take into account the attenuation with distance and amplification by deep/soft deposits, were used for the assessment of liquefaction.

- The Seed and Idris simplified procedure (National Research Council, 1985) for assessment of liquefaction potential, given the predominantly Standard Penetration Test data available from past investigations. The Sugawara (1989) method was used where Cone Penetration Test data was available.

- Verification of liquefaction potential using historical evidence compiled during the study.

The liquefaction potential was mapped using the assessment together with the surface geology and ground shaking hazard maps. The ground damage associated with liquefaction was also assessed, using the method of Tokimatsu and Seed (1987) to estimate subsidence, and historical evidence to predict areas likely to be subject to lateral spreading.

The hazard maps were prepared using a geographical information system (ArcCAD). The maps were prepared to scales of 1:10,000 for the Wellington City and 1:25,000 for other areas. A section of a typical liquefaction hazard map is shown on Figure 2.

Slope Failure Hazards

Opus International Consultants together with the Institute of Geological and Nuclear Sciences undertook an earthquake induced slope failure hazard study for the Wellington Regional Council. This included the urban areas and main transportation corridors (State Highways 1, 2 and 58) in the region. A specific methodology was developed for the assessment and mapping following a review of worldwide literature, and is described by Brabhaharan et al (1999). In summary, the assessment was based on :

- A review of historical records of earthquake induced slope failure in the Wellington region. This suggested that the threshold for significant slope failures in the Wellington region is generally Modified Mercalli (MM) Intensity VII, and for widespread slope failures is MM VIII to X or higher. The largest and most widespread failures in the Wellington Region during recorded history occurred in the 1855 Wairarapa Earthquake (magnitude 8), which caused MM X shaking in Wellington.

- Identification of factors that contribute to slope failures during earthquakes, such as slope angle, slope modification (cut slopes), geology, past landslides etc, and compilation of factor maps from available information and site reconnaissance by an engineering geologist.

- Integration of factors to derive slope failure hazard rating.

- Review of slope failure mechanisms and historical evidence.

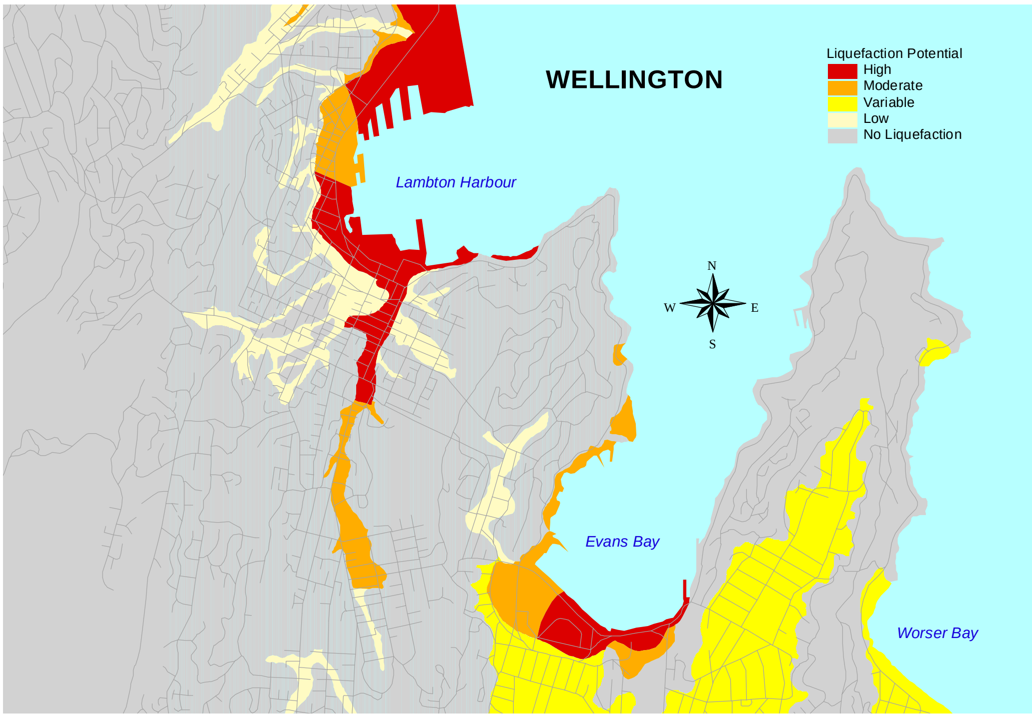

Figure 2 : Typical Liquefaction Hazard Map

- Assignment of factor values and weightings and integration to obtain a slope failure susceptibility rating

  $$R_s = \Sigma (F_i \cdot W_i) \qquad \text{(Equation 1)}$$

  where F_i represents factor values for the factor 'i' and W_i represents associated weightings, for factors – slope angle, slope modification, slope height, geology, past landslides and groundwater.

- Three earthquake scenarios – a magnitude 7.5 earthquake on the active Wellington Fault, a magnitude 7 distant earthquake event (some 100 km away) and an Intermediate Scenario, an earthquake causing MM VII to VIII shaking in the Wellington Region.

- Mapping of slope failure susceptibility using the factor maps and the slope failure susceptibility rating derived by combination of the factors.

- Presentation of slope failure potential for the three earthquake scenarios considered. The slope failure maps were calibrated using the historical evidence of slope failures during earthquakes.

Slope failure hazard maps were prepared to a scale of 1:25,000, and have been published by the Wellington Regional Council. A typical section of the slope failure hazard map is presented in Figure 3.

Hazard Maps

The liquefaction and slope failure hazard maps were prepared using ArcCAD, which is compatible with the ArcInfo geographical information system.

The hazard information is held in Wellington Regional Council's ArcInfo GIS system, and is available for earthquake risk studies and risk management by other territorial authorities. The information in GIS format enables it to be readily used with GIS information on infrastructural assets and lifelines, to assess the risk to these assets.

The hazard maps have also been published and are useful for engineering as well as information and educational purposes, to improve the awareness of the community to earthquake hazards.

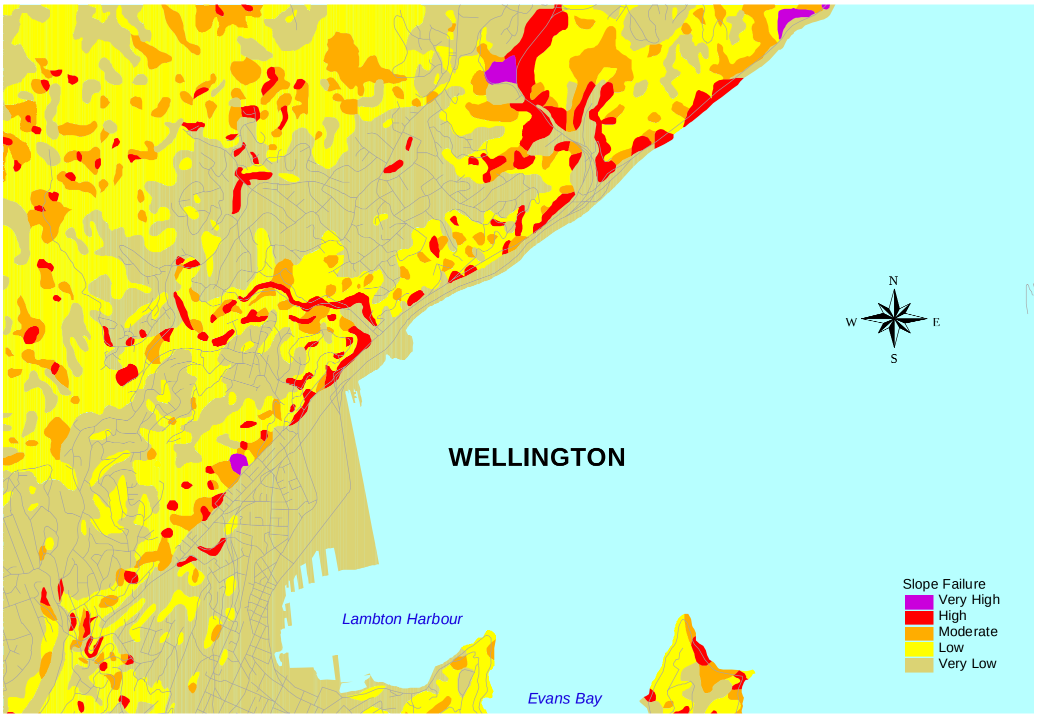

Figure 3 : Typical Slope Failure Hazard Map

RISK ASSESSMENT STUDIES

Regional Risk Assessment

The earthquake hazard information enabled a regional study of the risk to buildings (residential and commercial), emergency facilities and people, by Opus International Consultants in 1995. This study was commissioned by the Wellington Regional Council to assess the earthquake risk in the Wellington Region. The study presented earthquake damage costs and possible number of deaths and injuries likely in selected earthquake scenarios, and the geographical variation of these risks. The study helped increase the awareness of the potential impact of earthquakes on the population.

Lifeline Studies

The Wellington Engineering Lifelines Group (Centre for Advanced Engineering, 1991) carried out initial studies of the earthquake hazards to lifelines. This was further developed using the hazard maps prepared for the Wellington Region. Overlaying the lifeline network on the hazard maps enabled a quick appreciation of the risks to the network on a qualitative basis and identification of critical areas and interdependencies between lifelines (Wellington Earthquake Lifelines Group, 1993). The lifelines studies made a major contribution in bringing together lifelines authorities and companies, and by highlighting the risks to lifelines from earthquakes. Similar lifelines groups have since been set-up in other cities of New Zealand, such as Christchurch, Napier and Auckland.

A more detailed study to quantify the potential damage costs for Wellington Region's bulk water supply and telecommunications networks was carried out by Opus International Consultants. This was based on the ground shaking hazard maps as well as the likely ground damage assessed from the liquefaction ground damage maps and the raw data collected for the liquefaction hazard study. Slope failure ground damage was also assessed based on the terrain in which the water mains and telecommunications cables are located. The ground damage estimates together with predicted damage rates (such as breaks per kilometre for pipes) from published literature and judgement enabled an assessment of the potential damage costs.

Infrastructural Risk Studies

A number of territorial authorities have commissioned studies to assess their exposure to earthquake hazards. One of the earliest comprehensive studies was carried out for the Porirua City Council by Opus International Consultants. GIS data from the hazard studies, and infrastructural asset information for buildings, roads, water supply and drainage were used to assess the earthquake risk during four earthquake scenarios.

Similar studies have just been completed for Upper Hutt City Council by Opus International Consultants. The Upper Hutt integrated earthquake risk study has been carried out using a geographical information system (ArcCAD) by developing GIS models which derive the damage costs for each of the identified infrastructure layers, for a given input earthquake MM Intensity. The models use parameters linked to the earthquake hazard maps prepared for the Wellington Regional Council, and is flexible to accommodate refined data on the infrastructure as it becomes available, new infrastructural assets that may be added to the network, or refinement of the hazard information. This provides a valuable tool for ongoing management of the risks to Council's assets. The assets included roads, bridges, water supply, drainage, pump stations, reservoirs and buildings.

EARTHQUAKE RISK MANAGEMENT

Risk Management Options

The ultimate objective of earthquake hazard and risk studies is to manage the risks posed by earthquakes to the people and the built and natural environments. The risks from earthquakes cannot be eliminated completely in any society. The cost of risk reduction can be considerable and complete elimination may not be practical, affordable or economically viable. Therefore there is a strong need for risk management.

Brabhaharan (1998) presented possible earthquake risk management options. The risk can be managed by :

- Mitigation
- Avoidance or Redundancy
- Acceptance and Preparedness

Often a combination of measures may be appropriate. Risk can be defined as :

Risk = Hazard Likelihood x Consequences *(Equation 2)*

The likelihood of the earthquake, at any location cannot be changed. Avoidance considers means of relocating to an area with a lower hazard. Much of earthquake risk management involves ways of managing the consequences of the hazard to our asset or community of interest.

A number of initiatives have been taken in the Wellington Region, to manage the risk associated with earthquakes. The risk management initiatives are illustrated using selected examples.

Porirua City Council Planning Criteria

Porirua City Council have initiated risk management initiatives to reduce the risk to the community in the long term, based a studies of potential risk management options prepared by Opus International Consultants. The risk management initiatives were implemented through planning measures, discussed below.

Seismic Hazard Zones

Seismic Hazard Zones were derived from the individual earthquake hazard maps to show areas which had earthquake hazards that required specific consideration during development, beyond design to normal building code requirements. These zones included areas of significant amplified ground shaking, liquefaction, slope failure and fault rupture. The zones were then related to the property boundaries from cadastral maps and installed in Porirua City Council's geographical information system, and became part of the District Plan. This enables council officers to query individual properties and where located within the seismic hazard (consideration) zone, to provide information to developers as part of Land Information Memoranda (LIM) or Project Information Memoranda (PIM).

Criteria for Control of Development

The District Plan also includes specially developed criteria for development in areas with significant hazards beyond that covered by building codes and depending on the nature of the development. For example, facilities that will attract significant number of people will need to meet special requirements given the higher risk.

Upper Hutt Rural Road Risk Management

Upper Hutt City Council has a rural road network that is highly vulnerable to earthquakes as well as storms. To plan for management of the rural road network and the associated risks, a rural road risk study was carried out to assess the risks (damage and disruption costs), mitigation measures and the benefits and economics of risk mitigation. The study carried out by Opus International Consultants used the previous earthquake hazard maps, supplemented by site reconnaissance to characterise the road in terms of the potential impact of earthquake and storm hazards on the road network. Road damage costs and potential mitigation costs were considered for each road category, and the likelihood of failure and potential disruption costs were assessed. The road characterisation was mapped onto GIS, and the road damage, disruption and mitigation costs were assigned to derive total costs as well as the distribution of damage costs for the road network using GIS techniques.

To prioritise mitigation measures, risk-economic analyses were carried out similar to that proposed by Brabhaharan and Vessey (1992). The analyses gave benefit-cost ratios, with benefits being calculated as the savings in damage and disruption costs from carrying out mitigation measures, and the cost being that for implementing mitigation measures. As with the case of such mitigation work, the benefit / cost ratios were generally less than 1, given the high mitigation costs, relatively low traffic volumes along the rural roads and the relatively low frequency of large earthquakes. Figure 4 shows a section of the rural road network, and the hazard characterisation for roads.

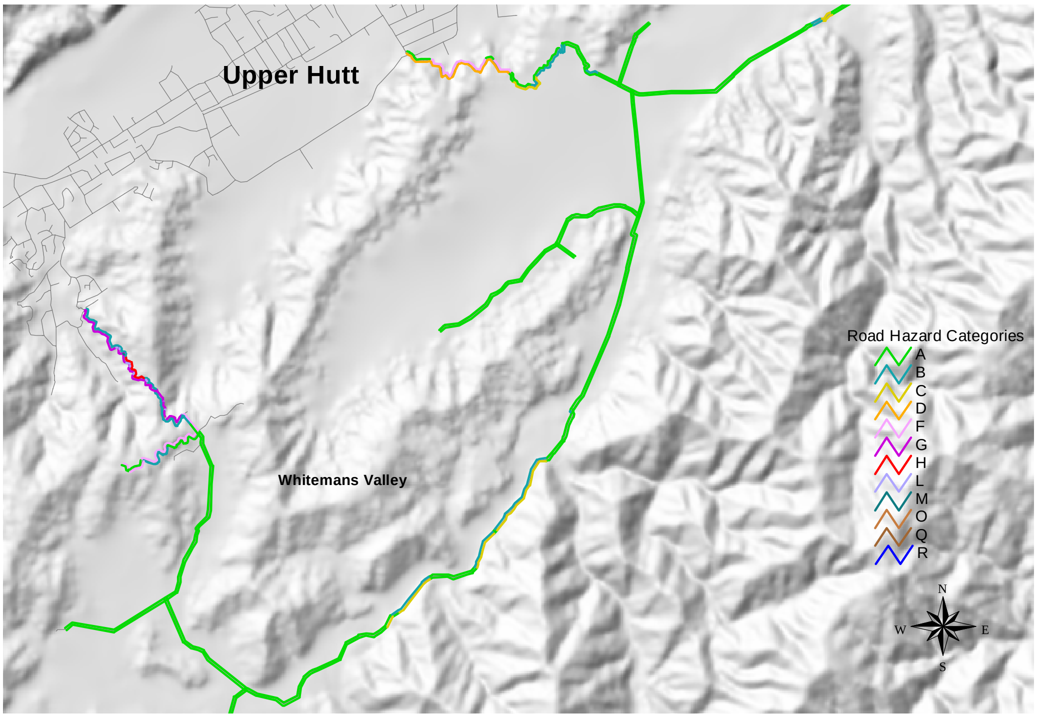

Figure 4 : Section of Rural Road Network showing assessed Road Hazard Categories

In earthquake risk management, often factors other than risk-economics will need to be considered, given the severe social impacts of such events. Nevertheless the risk-economic assessments provide a framework for prioritisation for mitigation in conjunction with other non-financial considerations. In these rural roads in steep terrain, the mitigation costs are often of similar magnitude as damage costs. Given the uncertainty as to the events and the likely location of failures, it would be prudent to carry out mitigation of the most vulnerable areas and undertake emergency planning to manage the remaining risks by prompt remedial works after events.

CONCLUSIONS

The Wellington Region of New Zealand has a high risk from earthquakes. The Wellington Regional Council has a proactive strategy to reduce the adverse effects of natural hazards to an acceptable level, and a comprehensive programme of earthquake assessment and mapping studies have been undertaken over the past decade.

Assessment and hazard mapping techniques have been developed for earthquake induced ground damage hazards – liquefaction and slope failure, and have been applied to the hazard mapping in the Wellington Region. The studies have been based on a technical assessment as well as verification using historical records. These have the potential to be used in hazard mapping for other areas.

The hazard identification studies have allowed the assessment of earthquake risks for a range of infrastructural assets and lifelines. These have allowed the risks to be quantified and used for risk management purposes. This has also been used extensively for insurance loss estimates. Planning measures can be used to encourage consideration of earthquake hazards and risk management for new development. Porirua City Council has taken such an approach.

Risk mitigation can often have a high cost. Risk-economic assessments can be useful to consider the economic benefits from mitigation. This together with non-financial factors can be used to prioritise mitigation and make decisions on appropriate risk management strategies.

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REFERENCES

Brabhaharan, P and Vessey, JV (1992). *Development of Economical Solutions to Mitigate Geotechnical Risks : Waipaoa Water Treatment Augmentation Plant.* 6th Australia-New Zealand Conference on Geomechanics. Christchurch. February 1992.

Brabhaharan, P, Hastie, WJ and Kingsbury, PA (1994). *Liquefaction Hazard Mapping Techniques Developed for the Wellington Region, New Zealand.* Annual NZNSEE Conference, Wairakei, 18-20 March 1994.

Brabhaharan, P (1998). *Hazard Assessment and Risk Management for Earthquake Disaster Survival.* Invited Keynote Address. Engineering in Natural Disasters – Survival, Relief and Restoration. Conference '98. 25-27 September 1998. Rabaul, Papua New Guinea. Institution of Engineers, PNG.

Brabhaharan, P, et al (1999). Earthquake slope failure hazards in the Wellington Region. Under preparation.

Centre for Advanced Engineering (1991). *Lifelines in Earthquakes – Wellington Case Study*. August 1991.

Gilmour, A and Stanton, B (1990). *Tsunami Hazard in the Wellington Region.* Regional Natural Disaster Reduction Plan. Wellington Regional Council. June 1990.

National Research Council (1985). *Liquefaction of Soils during Earthquakes*. National Academy Press.

Tokimatsu, K and Seed, HB (1987). *Evaluation of Settlements in Sands due to earthquake shaking*. Journal of geotechnical engineering. ASCE Vol 113, No 8, pp 861-878.

Wellington Earthquake Lifelines Group (1993). *1993 Report*. Wellington Regional Council. November 1993.

Wellington Regional Council (1995a). *Earthquake and Geological Hazard Mitigation Strategy*, Wellington Regional Council. December 1995.