Liquefaction Hazards in the Western Bay of Plenty

P Brabhaharan
B Sc Eng (Hons), M Sc Eng, MIPENZ, MICE, MIEAust, C Eng, CP Eng, Registered Engineer
Principal, Geotechnical Engineering & Risk, Opus International Consultants Limited, Wellington
J Thrush
BE (Hons), GIPENZ
Civil Engineer, Opus International Consultants Ltd, Wellington

Abstract: Liquefaction hazard mapping was carried out for the Tauranga and Western Bay of Plenty Districts as part of an earthquake microzoning study for the Western Bay of Plenty Engineering Lifelines Group. Liquefaction potential was assessed using current semi-empirical procedures, based on past site investigation information collated and supplemented by additional investigations to fill gaps in the information. Liquefaction hazards were mapped from the point estimates and the geology of the area, using a geographical information system (GIS).

The liquefaction hazard is variable with a high potential for liquefaction in the recent estuarine / marine / alluvial sediments including pumiceous sands and a low potential in the coastal sand deposits. Volcanic ash is generally resistant to liquefaction. Ground damage (subsidence and lateral spreading) from liquefaction was also mapped, as this is an important contributor of damage to lifelines. The hazard maps provide a basis for assessment of the risk to lifelines from liquefaction.

INTRODUCTION

Lifelines such as road, rail transportation, communications, electricity, gas, water supply, sewage systems are critical to the survival of communities after natural hazard events such as earthquakes. Therefore it is important to ensure that these facilities can survive or can be readily brought back into service after such events. The Western Bay of Plenty Engineering Lifelines Group is facilitating risk management for lifelines in the area comprising the Tauranga and Western Bay of Plenty Districts. As part of their strategy to promote the management of risks to lifelines, Opus International Consultants (Opus) and the Institute of Geological and Nuclear Sciences (GNS) were engaged to undertake an earthquake microzoning study for the Western Bay of Plenty area.

The microzoning study will provide information to assess the risk from earthquakes to lifelines in the region. The microzoning study included assessment and mapping of the earthquake hazards – active faults, ground shaking and liquefaction. Earthquake induced slope failure and tsunami hazards will be the subject of separate studies. This paper presents the assessment and mapping of the liquefaction hazards for the study area.

DEFINITION AND MECHANISM

Liquefaction includes all "phenomena giving rise to a loss of shearing resistance or to the development of excessive strains as a result of transient or repeated disturbance of saturated cohesionless soils" (National Research Council, 1985). Ground shaking associated with earthquakes gives rise to an increase in the porewater pressure in saturated, loose, mainly cohesionless soils, leading to earthquake-induced liquefaction. In soils where the increasing porewater pressures cannot dissipate rapidly, and become equal to the overburden stress, the soil particles no longer have inter-particular friction, and the soil liquefies, losing most of its strength. Sufficient strength and duration of shaking are necessary to cause significant porewater pressure increase in the soils and to reach the state of liquefaction.

Liquefaction most commonly occurs in saturated loose sands and silty sands. Increasingly it has become apparent from observations in earthquakes that loose sandy gravels and low plasticity sandy silts and silts can also liquefy (Brabhaharan et al, 1994).

LIQUEFACTION HAZARD MAPPING METHODS

Level of Mapping

Liquefaction hazard mapping has gained importance in areas subject to earthquakes, given the high level of damage that can result from liquefaction. This has been widely used for a variety of purposes such as land use planning and risk assessment. In New Zealand, hazard maps have been used for lifeline risk assessment, insurance loss studies and land use planning. A summary of the literature on liquefaction hazard mapping was reviewed as part of the 1992-1993 liquefaction study for the Wellington Region (Brabhaharan et al, 1994).

A *Manual for Zonation on Seismic Geotechnical Hazards* was prepared by the technical committee for earthquake engineering (TC4) of the International Society for Soil Mechanics and Foundation Engineering (Japanese Society for Soil Mechanics and Foundation Engineering, 1993) to provide guidance on standard approaches to the assessment of geotechnical earthquake hazards. This manual classifies zoning for geotechnical earthquake hazards into three grades :

- Grade – 1 General method using existing historical information and geology maps (low cost).
- Grade – 2 Detailed method using aerial photos, field studies and interview (moderate cost).
- Grade – 3 Rigorous method using geotechnical investigation and analysis (higher cost).

The grades represent different grades of zonation depending on the information used, and the potential use of the maps, and represent different levels of cost of preparation.

The Wellington study (Brabhaharan et al, 1994) methodology, adapted for Western Bay of Plenty study, used a combined approach with geotechnical engineering assessment using investigation data, verification of liquefaction based on historical records of liquefaction, and extrapolation of the point assessments using the geology and geomorphology of the area. The approach is similar to the Grade-3 level. However, the map was to a smaller scale appropriate for regional risk assessments, and the method minimises the cost of the zonation by making maximum use of available information on ground investigations from public and private sources, with only limited additional geotechnical investigations.

State-of-the-Art Liquefaction Assessment Methods

The liquefaction assessment methods have been further developed since the Wellington study. A workshop was held by the National Center for Earthquake Engineering Research (NCEER) based in the State University of New York at Buffalo, to bring together experts with knowledge of recent developments, and to put together the state-of-the-art methods for assessing liquefaction hazard (NCEER, 1997). The method using Standard Penetration Tests and Cone Penetration Tests adopted in the workshop is that proposed by Robertson and Wride (1998).

The Robertson and Wride method uses the Seed and Idriss semi-empirical approach, but has improved it based on a larger database of liquefaction records in past earthquakes. It incorporates correction factors for the fines content of the soil and plasticity.

Methodology Adopted for Western Bay of Plenty

The methodology adopted for the Western Bay of Plenty liquefaction hazard study was that developed for the Wellington study (Brabhaharan et al, 1994), tailored to incorporate recent refinements to the liquefaction assessment methods, and tailored to suit the information available and the requirements of this study.

This approach comprised:

- Review of historical records of liquefaction
- Data collection and additional geotechnical investigations
- Identification of areas susceptible to liquefaction

- Selection of key site investigation locations
- Selection of ground shaking hazard information
- Assessment and mapping of the potential for liquefaction
- Assessment and mapping of liquefaction induced ground damage.

REVIEW OF HISTORICAL RECORDS LIQUEFACTION

Johnston and Scott (2000) summarised a review of the available natural hazards information for the Western Bay of Plenty. In recorded history (since c. 1840), the largest shallow earthquakes in this region were the 1891 Waikato Heads earthquake and the 1932 Bay of Plenty earthquake, which had Richter magnitudes of about 6.0. The 1932 Bay of Plenty earthquake caused Modified Mercalli V (MM 5) intensity in Tauranga.

Fairless (1984) compiled case histories of liquefaction throughout New Zealand. No records of liquefaction in the Western Bay of Plenty area were identified in that study. This could be attributed to the lack of strong earthquake shaking in the Western Bay of Plenty study area during the relatively brief recorded history of European settlement in New Zealand. There are many historical records of liquefaction in New Zealand, including observations in the adjacent Whakatane District in the 1987 Edgecumbe Earthquake (Jennings et al, 1988, Pender and Robertson. 1987).

DATA COLLECTION AND GEOTECHNICAL INVESTIGATIONS

Data on ground conditions from past geotechnical investigations and studies were collected from the Councils and other organisations, with the assistance of the lifelines group project manager. Information held by Opus and GNS were also collated. The information collated and reviewed as part of this study included over 200 geotechnical / groundwater reports and well bore records from Environment BOP. The information was reviewed in relation to the known lifeline corridors, and gaps in the available information were identified. Further information was collected from other organisations by targeting these gaps. The locations were mapped in a geographical information system (GIS). A programme of geotechnical investigations, comprising comprised four boreholes with Standard Penetration Tests, nineteen Static Cone Penetration Tests (CPT) and laboratory classification tests, were carried out to fill remaining gaps in information along important lifeline corridors in areas identified as being susceptible to liquefaction.

LIQUEFACTION SUSCEPTIBILITY BASED ON GEOLOGY

Geology Maps

The geological map compiled by GNS was used to characterise the areas susceptible to liquefaction. The geology was compiled from three published geological maps of Healy et al (1964) at 1:250,000 scale, Briggs et al (1996) at 1:50,000 scale and Edbrooke (2001) at 1:250,000 scale. For the geological units that weren't common to all three maps, the legend of Edbrooke was adopted because of its finer subdivision of the Quaternary and Holocene Age geological units. The geology of the area comprises various ignimbrite flow sheets, which have been subsequently mantled by alluvium and volcanic ash. Soft estuarine sediments and alluvium have been deposited in flood plains and incised gullies that extend inland from the coast.

Liquefaction Susceptibility of Major Soil Units

The major soil types in the study area were characterised for liquefaction susceptibility.

Estuarine Deposits: Large areas of estuarine deposits are present in the study area, and comprise sands, silts and clays. The dominant silts and sands are susceptible to liquefaction, and a thickness of 5 m to 20 m or more of loose sediments are present in these areas.

Although fine-grained soils (silts) are more resistant to liquefaction, it is now recognised that low plasticity fine-grained soils such as silts can liquefy. For example, ground damage observations in Wellington during the 1855 Wairarapa Earthquake indicate that fine-grained soils liquefied in that earthquake (Brabhaharan et al, 1994). Even when liquefaction of very soft fine grained soils does not occur, these soft soils can undergo severe loss of strength during ground shaking, and can give rise to ground strains and lateral spreading similar to classic liquefaction.

Volcanic Ash Deposits: The terrace areas from Tauranga to Katikati are covered with volcanic ash deposits, which comprise clays, silts and some sand layers. These are generally firm to stiff or medium dense. These materials are generally considered to be resistant to liquefaction due to the fine-grained plastic nature and the presence of some "welding effects" due to their volcanic origin.

Volcanic Grits and Pumiceous Sands: Coarser grained pumice deposits have been shown in recent studies to be susceptible to liquefaction (Shimizu, 1998 and Marks et al, 1998). Observations during the 1987 Edgecumbe Earthquake in the Eastern Bay of Plenty also showed that sand with significant pumiceous material had liquefied (Pender and Robertson, 1987). Therefore, localised loose sand layers that are present among the volcanic ash deposits may undergo minor liquefaction under strong ground shaking.

Older terrace deposits: The older terraces such as in the Te Puke area include sand deposits, which are moderately dense and are of limited thickness. The older deposits tend to have a lower susceptibility to liquefaction due to ageing effects, which could lead to some inter-particle bonding. These areas are only likely to liquefy in larger events and the associated thickness is smaller.

Coastal sand deposits: The coastal sands are generally medium dense to dense, consistent with their higher energy depositional environment. These are generally resistant to liquefaction, but may experience some liquefaction in large earthquake events.

Residual Soil from Ignimbrite Sheets: Various ignimbrite sheets are present in the area, and near the surface, they are completely weathered and are indicated to be clays and sands. There is limited information from these areas to assess the liquefaction. In some locations these comprise loose sands and silts which are likely to be susceptible to liquefaction. However, these may be localised and the predominantly these residual soils are likely to be dense or stiff and resistant to liquefaction. Given that there are limited lifelines through these areas, this uncertainty is less important.

LIQUEFACTION ASSESSMENT

Selection of Key Locations

Key locations of geotechnical information were selected from the large database of ground investigation locations, based on their quality, the susceptibility based on geology, and the lifeline corridors. Seventy-five key locations were chosen, and some assumptions, particularly regarding groundwater levels and particle size distributions were made to supplement the factual information.

Ground Shaking Hazards

Ground shaking hazards were compiled by GNS as part of the earthquake microzoning project. Peak ground acceleration maps had been derived for two uniform hazard scenarios of 10% probability of exceedance in 50 years (return period of 475 years) and 2% probability of exceedance in 50 years (return period of 2500 years). The uniform hazard ground shaking maps were used for the liquefaction assessment. Liquefaction depends on the magnitude of the earthquake and associated duration of shaking. The contribution to the uniform hazard comes from earthquakes with different magnitudes. Therefore, it is not appropriate to use the uniform hazard peak ground accelerations directly for the analyses. A method of weighting proposed by Idriss (1985), to modify the peak ground accelerations depending on the earthquake magnitude, was used by GNS to derive *magnitude weighted peak ground accelerations*. The magnitude weighted values then allow the use of the standard liquefaction charts based on an earthquake magnitude of 7.5.

Analyses

The liquefaction analysis was based on empirical correlation of cyclic stress ratio with Standard Penetration Test 'N' values or Static Cone Penetration Test cone resistances (q_c), for soils which liquefied and those which did not liquefy in past earthquakes (NCEER, 1997).

$$\text{Cyclic stress ratio} = 0.65 \,.\, a_{max} \,.\, \sigma_0 \,.\, r_d \,/\, \sigma'_0 \,.\, g \qquad (1)$$

where,

a_{max}	peak ground acceleration
σ_0	total overburden stress at the depth under consideration
r_d	stress reduction factor that reduces from 1 at the ground surface
σ'_0	effective overburden stress at the same depth
g	gravitational acceleration

The penetration test values were corrected for energy differences in the Standard Penetration Tests and overburden pressure. The fines content and Plasticity Index of the soils were used (and where not available assumed) to adjust for the increased liquefaction resistance associated with the proportion of fines and higher plasticity. The analysis indicated thickness of soils that are likely to liquefy at each of the key sites, and their potential for liquefaction.

Classification and Mapping

Liquefaction potential was mapped into the five classes in Table 1, depending on the likelihood of liquefaction in the two uniform ground shaking levels, the liquefaction thickness and extent of associated ground deformation.

Class	Liquefaction Potential	Description
1	No Liquefaction	Liquefaction unlikely in any scenario, except locally such as in stream deposits or fill.
2	Localised Liquefaction	Liquefaction is generally unlikely but there may be limited areas that are likely to liquefy in a large earthquake event.
3	Minor Liquefaction	No liquefaction likely in a 10% in 50 year earthquake shaking, but liquefaction of limited layers may occur in a 2% in 50 year shaking.
4	Moderate Liquefaction	Liquefaction is likely in both 10% and 2% in 50 year earthquake shaking, in localised areas or leads to limited ground damage.
5	Widespread Liquefaction	Liquefaction is likely to be extensive in both 10% and 2% in 50 year earthquake shaking and could lead to significant ground damage.

Table 1. Liquefaction Potential Classes.

The liquefaction hazard was then mapped by considering the point assessments of liquefaction potential and the extent of liquefaction based on the geographical spread of the point estimates and the geological extent of the soils. Part of the liquefaction hazard map is shown on Figure 1.

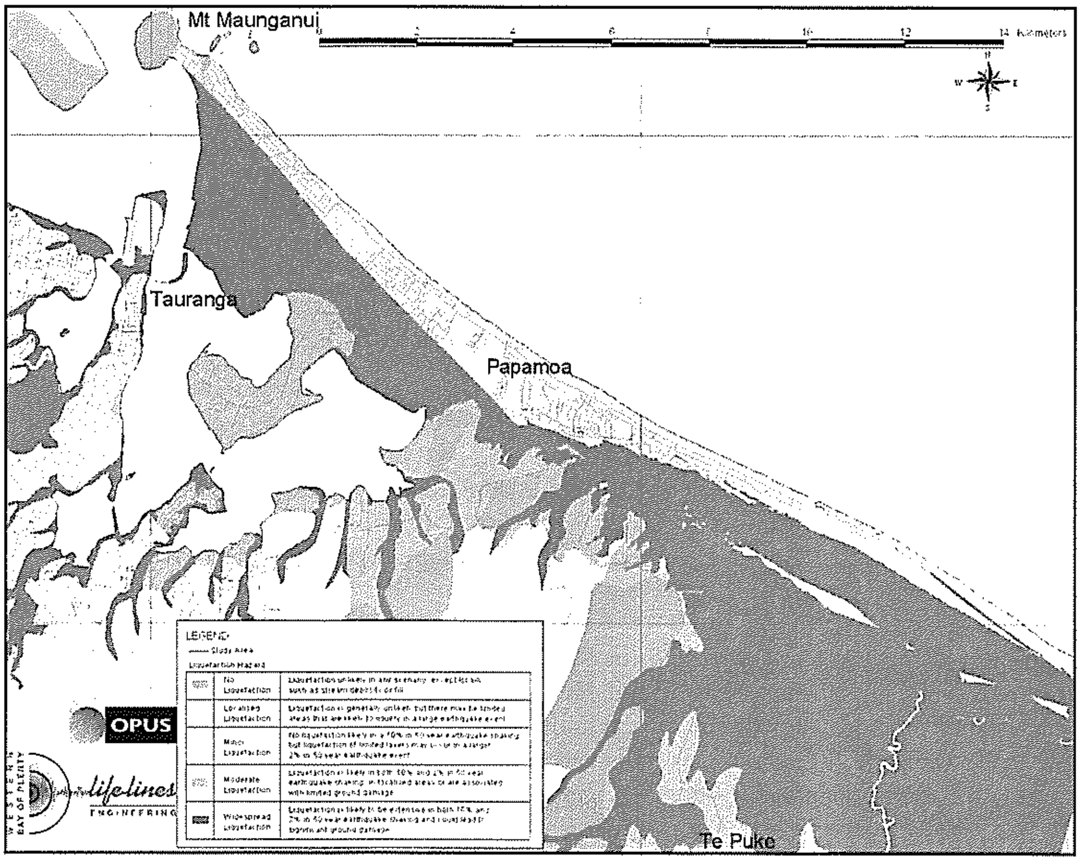

Figure 1. Part of Liquefaction Potential Map

LIQUEFACTION GROUND DAMAGE

Consequences of Liquefaction

The following consequences of liquefaction can cause damage to lifelines :

- Ground damage – subsidence, lateral spreading, flow failure, slope failure
- Bouyancy on buried facilities, exacerbated by flooding from ejection of water and sand / silt
- Foundation failure due to reduction / loss of bearing capacity
- Settlement of structures on liquefied materials

Liquefaction induced ground damage is an important contributor to the damage to most lifelines. The other consequences will depend on the form of the lifeline structures and their foundations.

Types of Ground Damage

Liquefaction can lead to ground damage in the form of :

- Subsidence of ground underlain by liquefied soils
- Slope failure or flow failure of liquefied ground
- Lateral spreading of liquefied ground, and of embankments on liquefied ground

Liquefaction resistant surface layers can reduce ground surface damage from liquefaction of underlying layers. However, such non-liquefiable surface layers may not preclude lateral spreading. Recent studies have indicated that lower permeability, liquefaction resistant layers overlying liquefiable soil layers may lead to the formation of water films at the interface, and can result in liquefaction of the overlying layers and increased lateral spreading.

The ground damage will depend on the liquefiable soils, their thickness, and the topography.

Ground Subsidence

Subsidence of the ground due to liquefaction was assessed using the method proposed by Ishihara and Yoshimine (1992), for each key location chosen for liquefaction assessment. These very approximate subsidence estimates range from less than 10 mm to over 1 m. Indicative magnitudes of ground subsidence for the different liquefaction potential classes in a 10% in 50 year earthquake shaking are given in Table 2.

Class	Liquefaction Potential	Order of Magnitude of Subsidence (mm)
1	No Liquefaction	None
2	Localised liquefaction	Variable but likely to be small.
3	Minor Liquefaction	Less than 100 mm
4	Moderate Liquefaction	100 mm to 300 mm
5	Widespread Liquefaction	Greater than 300 mm (possibly over 1 m)

Table 2. Liquefaction Induced Subsidence.

Lateral Spreading

Lateral spreading of ground has the potential to cause a greater magnitude of ground damage and consequential damage to lifelines. This could occur where liquefied ground can displace towards free surfaces such as river or stream banks and the shorelines. Any embankments (including bridge approaches) built on liquefiable ground are also likely to undergo lateral spreading. Severe damage to a road embankment due to liquefaction related lateral spreading during the 1931 Napier Earthquake is shown on Figure 2.

Figure 2. Lateral Spreading of Road Embankment in Napier Earthquake, 1931

The extent and magnitude of lateral spreading is difficult to assess for regional scale mapping. However, simple rules as to the magnitude and extent of lateral spreading, based on observations in historical earthquakes, were used to provide an indication of the lateral spreading ground damage that may occur, recognising that this is indicative only.

Classification and Mapping Liquefaction Ground Damage

The liquefaction ground damage hazards was mapped using ground damage (subsidence and lateral spreading) assessments, the liquefaction hazard and the proximity to river and significant stream banks. The liquefaction ground damage hazard classification is presented in Table 3.

Liquefaction Ground Damage Zone	Class Description	10% in 50 years	2% in 50 years
A	None	No liquefaction ground damage	
B	Localised minor	Localised minor subsidence	
C	Minor	Minor subsidence (less than 100 mm)	
D	Limited	Moderate subsidence (say 100 mm to 300 mm)	
E	Moderate	Large Subsidence (say greater than 300 mm)	
F	Large	Minor lateral spreading and moderate subsidence	Significant lateral spreading and moderate subsidence
G	Major	Significant lateral spreading and large subsidence	
H	Widespread	Significant lateral spreading and moderate subsidence.	Extensive lateral spreading and moderate subsidence
I	Extensive	Extensive lateral spreading and large subsidence	

Table 3. Liquefaction Ground Damage Classification.

Notes : Lateral spreading definitions

- Minor 10s of millimetres to 200 mm
- Significant 100s of millimetres to 1 metre
- Extensive up to few metres

The classification in Table 3 was used to prepare a map of liquefaction ground damage hazards. This provides a useful resource for the assessment of damage to lifelines. A section of the liquefaction ground damage hazard map is shown in Figure 3.

It is worth noting that significant lateral spreading damage was experienced in the 1995 Kobe Earthquake in Japan, and lateral spreading of the river banks were observed during the 1987 Edgecumbe Earthquake in the eastern Bay of Plenty.

SPATIAL INFORMATION MANAGEMENT AND MAPPING

The earthquake microzoning study involved collection and management of a large amount of information. The data was obtained in digital form or mapped, and managed within a geographical information system (GIS), in this instance ArcView. This enabled the information to be processed efficiently. The maps were produced in GIS format and are available for use in spatial GIS format, to facilitate the overlay of lifeline assets and assessment of the risk.

The maps were printed to a scale of 1:50,000 for the Tauranga urban area, with 1:250,000 scale maps showing the whole study area.

The maps have been prepared from a district scale study and can be used for the assessment of risk to lifeline networks at a district level. While they show areas of liquefaction and ground damage hazard, they should not be used to assume liquefaction or no liquefaction at specific sites. The maps should not be used as a substitute for site-specific investigations and assessments for individual sites and facilities. The classification of liquefaction and ground damage is indicative only. Identification of the limitations is important, so that hazard maps are not used out of context.

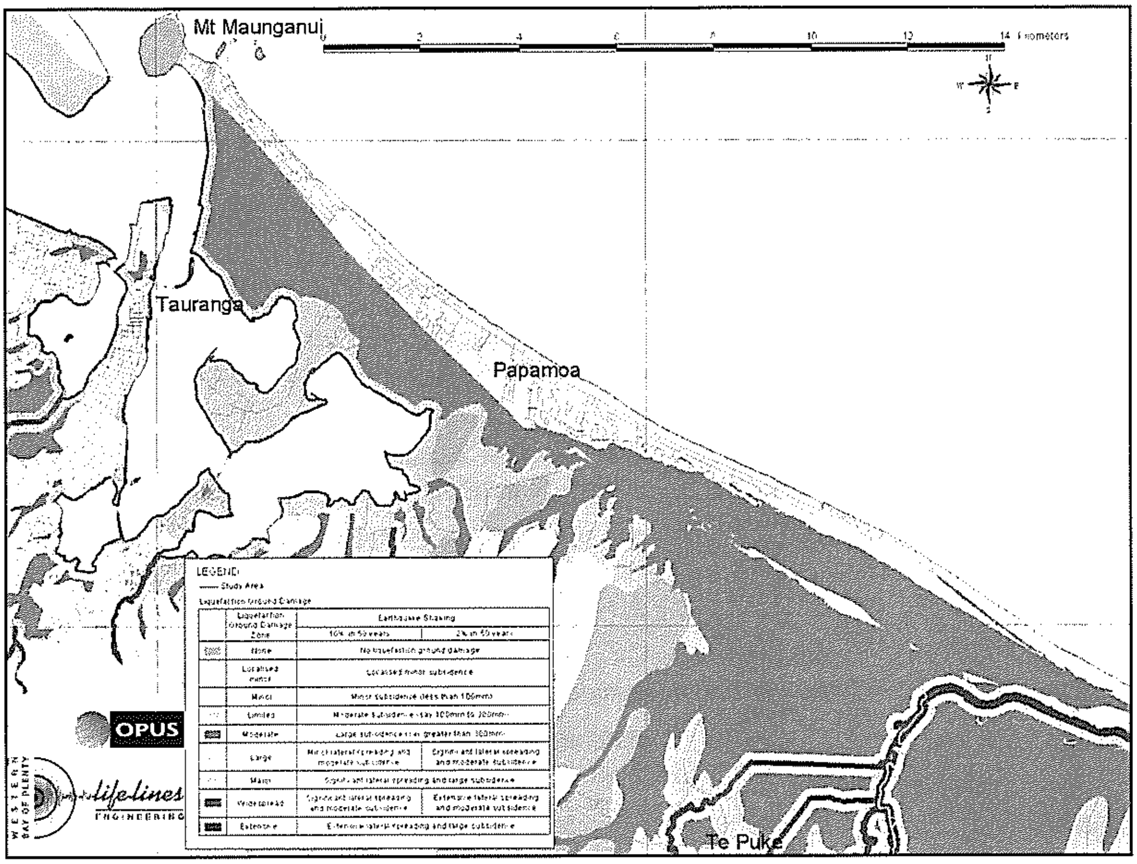

Figure 3. Part of Liquefaction Ground Damage Map

CONCLUSIONS & RECOMMENDATIONS

The geology of the Western Bay of Plenty area is complex with predominantly volcanic, estuarine, marine and alluvium deposits. The liquefaction assessment is based on a robust and efficient methodology, which was used to assess and map the liquefaction hazard using geotechnical information and the geology and topography. The liquefaction performance of volcanic soils is variable, with fine-grained volcanic ash deposits generally being resistant to liquefaction, and pumice sands generally being vulnerable to liquefaction. A key feature of the area is the presence of large areas of estuarine deposits that are vulnerable to liquefaction. Liquefaction induced ground damage was also mapped as lifelines are generally vulnerable to ground damage.

The methodology used provides a rational approach to prepare liquefaction hazard information suitable for the assessment and management of the risk to lifelines.

Further research into the liquefaction performance of volcanic soils, in particular the volcanic ash deposits would be valuable in refining the liquefaction hazard in volcanic regions.

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