LIQUEFACTION RISK EVALUATION MODELLING FOR HAWKES BAY REGION, NEW ZEALAND

A. King(1), B. Rosser(2), I.Matcham(3), S. Dellow(4), S. van Balegooy(5), V. Lacrosse(6)

(1) *Engineering Risk Specialist, GNS Science, a.king@gns.cri.nz*

(2) *Position, GNS Science,* b.rosser@gns.cri.nz

(3) *Software Architect and Developer, Jumbletree ,iain@jumbletree.com*

(4) *Engineering Geologist, GNS Science,s.dellow@gns.cri.nz*

(5) *Senior Geotechnical Engineer, Tonkin and Taylor Ltd,* s.vanbalegooy@tonkin.com

(6) *Geotechnical Engineer, Tonkin and Taylor Ltd,* v.lacrosse@tonkin.com

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Abstract

The significance of liquefaction induced damage during earthquake attack was clearly demonstrated during the Canterbury Earthquake Sequence [1] and resulted in the need for a uniform approach to be made to evaluate liquefaction hazard to provide a consistent basis for applying future building and land-use planning controls to mitigate or avoid any such future recurrence of the losses generated across Canterbury. This paper outlines the approach used to evaluate the risk from liquefaction to the Hawkes Bay Region on the east coast of New Zealand's North Island.

Two concurrent strands of work are reported, namely the identification of the liquefaction hazard under hazard various severities of shaking, and the potential losses and consequences of damage resulting therefrom. Determination of the liquefaction hazard involved the creation of liquefaction hazard zones based on their geomorphic characteristics, the crustal thickness (depth to groundwater) and the near-surface geotechnical profile (composition and density profiles). The potential losses were derived using the RiskScape regional risk evaluation tool with the building and infrastructural presence within the community being depicted within a GIS environment, and their vulnerability to both shaking and differential ground deformation assigned from known or assumed key attributes.

Keywords: Liquefaction: Damage: Risk: Regulatory Controls:

1. Introduction

The Canterbury Earthquake Sequence raised national awareness of liquefaction and its potential damage to buildings and infrastructure. This, in combination with proposed changes to the New Zealand Resource Management legislative framework [2] to include the consideration of natural hazards in land-use planning regulations, has resulted in the need for a uniform approach to be developed for the evaluation of liquefaction across New Zealand.

This paper reports on work that was undertaken over a two year period (2013~15) in conjunction with the Hawkes Bay Regional Council and the four local territorial authorities within that region [3]. The Hawke's Bay region is located on the east coast of the North Island of New Zealand. It is within New Zealand's high seismicity zone and was last subjected to a severely damaging earthquake in 1931 (M7.8) experiencing 1.5m of uplift across the Heretaunga Plains where the major urban centres of the Hawke's Bay are located. The geological setting of the Heretaunga Plains is a forearc basin where generally aggrading river systems flow into the basin that is subject to episodes of seismically controlled uplift and subsidence. Due to the 1931 uplift the current lagoon is much smaller than it was prior to the earthquake. The three major river systems that fed into the former Ahuriri lagoon now have engineered courses directly into Hawke Bay primarily as a flood protection measure. The deposition of soft, fine-grained, sedimentary deposits over the short geological past (Holocene), in combination with the high seismicity and the close proximity to the tectonic plate boundary (40 km offshore with a very shallow dip angle so it is 15-25 km deep beneath the region), and shallow groundwater, combine to create a potentially high liquefaction hazard.

An important consideration underpinning the study was to move beyond hazard and loss evaluation in consideration of risk, the required link being the likelihood of the event and therefore the projected loss Thus the simple potential for liquefaction is not an adequate indicator of when intervention may be required but is required to be considered in conjunction with how likely such an occurrence may be and whether, in this context, the consequences are 'tolerable' or 'intolerable' The Canterbury experience has shown severe liquefaction substantially increases the cost of repair to assets and infrastructure but is unlikely to raise the life-safety risk levels (i.e., it does not generally increase the likelihood of building collapse in the context of New Zealands' residential building stock)). As such regulatory intervention policies need to defer the onset of damage while accepting such damage for more severe events with longer return periods. The study was able to place before decision makers representations of how damage distribution was influenced by the severity of shaking and when and where regulatory intervention would be appropriate.

The **RiskScape** Regional Risk evaluation tool [4] was used as the delivery tool for the study. While it contained the ability to evaluate and present shaking loss results from earthquakes, it required the development of a specific **liquefaction module** and changes to the engine driving the model to evaluate additional 'triggered' losses to combine both shaking and liquefaction losses and damage projections. The Liquefaction Module computes differential ground deformation for each location based upon the ground shaking intensity derived from the Earthquake Shaking Module [5]. It then determines the damage increment and associated loss increment for each building using the appropriate liquefaction vulnerability functions.

The primary challenge faced within this study was the low resolution of geotechnical investigation results available to prescribe site conditions, contrary to the high (individual building) level at which loss evaluation was to be undertaken. This is the situation across most of New Zealand and a focus of the study was to develop a rational basis to capture available data, group this, and apply the resulting grouped bands to locations where site specific data is missing.

2. The Risk Evaluation Framework

The migration of 'loss' to 'risk' requires the likelihood of any specific action occurring to be considered and included in any model. Since liquefaction requires dynamic earthquake motions to occur before the phenomenon is triggered, it was necessary to evaluate the condition of the built environment subject to shaking and then add damage from ground deformation associated with liquefaction if applicable. The model evaluates the severity of ground motion at each asset location (circa 95,000 buildings, 150,000 people, 700 km pipes, 2000 km roads with around 150 bridges) and calculates the shaking damage and loss. The shaking severity (PGA) at each location is then passed to the liquefaction module wherein the calculated vertical displacement and lateral spread severity were used to assign a Differential Displacement Index (DDI) to each asset location and the liquefaction derived damage and loss is added to the shaking damage and loss.

The results of the study were recognised as needing to serve at least three specific sectors namely

1. **Building consent officials and land use planners:** – requiring pre-event controls (constraints) where additional site investigation and engineering mitigation was practical and thus a conservative approach was acceptable; Risk concepts are not well understood with avoidance or pre-event mitigation of primary interest.
2. **Civil defence and emergency responders**: Requires realistic event simulation for response planning and community resilience evaluation and strategy development under their obligations from the National Civil Defence and Emergency Management authority [6] – primarily interested in people and damage particularly to critical facilities and community services. The location and distribution of damage and disruption is also important as is the ability to test the effectiveness of alternative countermeasures. Costs, while important to enable priorities to be established, are of secondary importance) .
3. **Financial Risk Transfer agencies** (insurers and financial officers): Requires recurrence-interval based financial loss projections – cost is paramount and risk concepts are well understood.

To meet the needs of the land-use planners and building consent officials, it was necessary to identify the event return period where regulatory intervention was appropriate. With the premise that liquefaction was ‘damage’ rather than ‘safety’ orientated, it was recommended that regulatory intervention be promulgated when the return period of ‘significant damage’ (being DDI 2 for light concrete and DDI 3 for all sub-floor foundations) is anticipated. With the sparsity of high resolution data, such intervention is expected to be a requirement for detailed site investigations be undertaken to verify site specific properties to confirm ground deformation projections. For this sector maps have been produced on the basis that the target PGA value, adjusted where necessary for site class variations, is applied everywhere across the whole portion of the region for which it was developed.

To meet the needs of response planners and risk transfer agencies (insurance or otherwise) a suite of six specific events was generated, scaled to match the target PGA value provided from the National Seismic Hazard Model. At least one of these scenarios had an epicentre at that specified location and was located at an assumed depth and magnitude to meet the target PGA value. The other 5 scenarios are for events within the nominated magnitude bands coincident with those provide by the model interrogation. These latter 5 scenarios would each be conservative (i.e. result in ground motions within their epicentral location which are stronger than the target PGA required, and therefore result in greater damage to assets nearer the epicentre than those predicted.

3. The Risk Derivative of the Seismicity Model

The approach used was to identify five specific return periods (namely 25, 100, 500, 1000 and 2500 years) and interrogate the National Seismic Hazard model operated by GNS Science [5] to evaluate the severity of earthquake motions at three sites across the region (being locations coincident with the centroid of the three population centres). This interrogation resulted in the Peak Ground Acceleration (PGA) and the proportional contribution of various earthquake magnitudes being determined, as indicated in Table 1. As expected, the nominated PGA value could be generated either by local, small magnitude earthquakes, or more distant moderate or large magnitude events. Since the Liquefaction Severity Number discussed below uses event magnitude as a proxy for the duration of shaking, this distinction is particularly relevant for liquefaction studies such as this.

The Risk Evaluation Framework required the inclusion of earthquake event sets which met each of the PGA results for each of the five nominated return periods and for each of the three nominated locations. For each combination of the above, six specific earthquakes were identified as representing the range of significant contributors to damage and thus losses. One such event was to be located specifically at each nominated location, with the variables of magnitude and depth being used to match the surface PGA in this situation. For longer return period motions, significant motion contributions were resulting from events of magnitude 6+ and in these situations such events were located on one of the several known faults within the region. For return periods 1000 years and greater, where significant contributions were coming from events with magnitude 7 and above, at least one of the suite was located on the subduction zone interface which extends beneath the region at a depth of approximately 15~25 km.

Table 1 Napier/Hastings Return Period Target Event PGA
& Event Magnitude list in order of contribution dominancy

Napier/Hastings Site Class D					
	Return Period (years)				
	25	**100**	**500**	**1000**	**2500**
Unweighted PGA (g)	0.14	0.25	0.42	0.51	0.64
Magnitude Contribution	5.4, 5.6, 5.8	5.4, 6.2, 5.6	6.2, 7.6, 5.4	7.6, 6.2, 5.4	7.6, 6.2, 5.4

(Note Similar tables were developed for Wairoa and Central Hawkes Bay)

4. The Liquefaction Module

The liquefaction module required the **liquefaction hazard** (4.1) at each asset location to be available along with the **liquefaction vulnerability** (4.2) relationship for all assets under consideration. The module would accept ground shaking intensity (PGA) as input (Table 1), generate vertical displacement and thus inferred differential displacement across each asset footprint, grouping these into their respective Differential Displacement Index (DDI) classes and by reference to the asset vulnerability class, establish the incremental damage enhancement and loss projection for each asset at its specified location (Table 2). Damage and loss increments were then added to the shaking damage and loss projections for that asset and the resulting combined totals presented in both graphical map form (for location context) or in aggregated tabular form (for further analytical evaluation).

4.1 Liquefaction Hazard

Assessing liquefaction hazard for use of the liquefaction module required the models/maps to be developed as described in the following sections:

4.1.1 Surface Geomorphological Mapping:

A surface geomorphological map of the region was developed and checked against subsurface data from CPT probes and borehole data. The sedimentary origin of the near-surface sediments (1-5m depth) were mapped and similar areas grouped together. The resulting geomorphic map shown in Figure 1a . Some areas were eliminated as having no or low liquefaction hazard because of grain-size attributes of the underlying sediment. Based on the landform, liquefaction is not expected in gravel-dominated alluvium or will not occur on hill slopes. The remaining areas were further evaluated specifically for liquefaction using cone penetration test (CPT) data characterise the upper 20 m of subsurface geology of the various geomorphological map units. Further areas dominated by non-liquefiable gravels were identified and eliminated and basin fringe areas with shallow bedrock were also identified and eliminated resulting in Figure 1b. The borehole data confirmed a lack of heterogeneity between the sands, silty sands and silt layers across the Plains, making extrapolation between specific test locations uncertain.

4.1.2 Liquefaction Susceptibility Number (LSN) Development

The susceptibility of a soil to liquefaction depends on its compositional characteristics and state in the ground. Factors affecting this include history or age and geologic environment (Idriss & Boulanger, 2008). Soils that are cohesive in nature such as clays with high plasticity are not are susceptible to liquefaction. The susceptibility of soils to liquefaction (strain under cyclic loading), is typically assessed based on the proportion of active clay minerals in the soil and the plasticity of fine grained clay particles. These are combined to define a "cut-off" between soils that are, and are not, susceptible to liquefaction.

The soil behaviour index (I_c) as determined from Cone Penetration Test (CPT) testing was used as a screen to identify soils that are likely to be susceptible to liquefaction. An I_c -cutoff of 2.6 was used for the CPT-based liquefaction analyses undertaken for the Hawke's Bay liquefaction hazard study, this being consistent with Robertson & Wride, [7] as differentiating soils that are typically not susceptible to liquefaction and ratified by Lees et al. [8]. The Ic value was calibrated to laboratory test results that were carried out on soil samples obtained from drilling adjacent to the CPT locations where these were available, with the further process of screening susceptible soils based on plasticity of the soils, as described in terms of a soil's plasticity index (Atterberg limits) and water contents determined from laboratory testing (Bray & Sancio, [9]).

The liquefaction vulnerability/susceptibility parameters LSN and S_{V1D} proposed by van Ballegooy et al. [10, 11] were calculated for each CPT using the following principles:

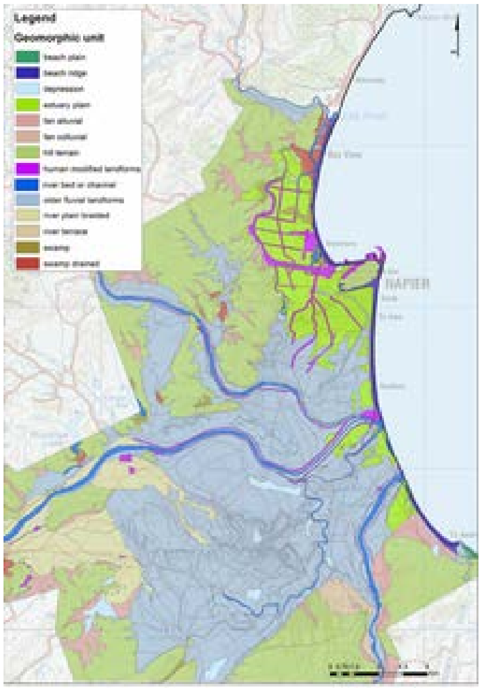
- Boulanger & Idriss [12] triggering method;
- Zhang Robertson & Brachman [13] calculated volumetric strain equations;
- Input parameter probability of liquefaction (PL) = 15% with respect to the vulnerability liquefaction triggering curves. (refer to Lacrosse et al., [14]
- I_c cut-off = 2.6 (i.e., soils with I_c above 2.6 are considered too clay-like to liquefy following the recommendations of Robertson & Wride [7] ;
- Fines Content (FC) –I_c correlation with a fitting parameter CFC = 0 (from Boulanger & Idriss [12],);
- Depth to groundwater from the model discussed below.
- Magnitudes = 5, 6, 7 and 8;
- PGA = 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0g.

A total of 714 CPTs were available for this project, 590 of which were used as they provided at least 5 m of raw data. CPT data were analysed to a depth of 10 m. The CPTs are largely clustered in the Hastings area, and the industrial areas of Napier city and Havelock North but elsewhere are scattered and sparsely to very sparsely distributed refer Figure 1b. The CPT data range in depth from 1 m to 29 m (below the ground surface) with an average depth of 9.80 m. The deepest CPT reaches to around 21 m below sea level.

LSN and S_{v1d} curves were developed for each CPT result following the procedure outlined by van Ballegooy et al., (2015). These were initially grouped to align with the Geomorphology maps discussed above and evaluated for outliers and anomalies. Some adjustments were applied to the liquefaction zone boundaries to reduce the uncertainty spread of the resulting curves. The liquefaction hazard zone maps shown in Figure 1d were applied to the Napier/Hastings area, with similar maps developed for the Central Hawkes Bay and Wairoa districts, albeit with less CPT data. A set of LSN curves was developed for each of the nominated earthquake magnitudes (5, 6, 7 and 8) a sample of which are shown in Figure 2 which show both the mean and distribution 15^{th} and 85^{th} percentiles) of the resulting curves.

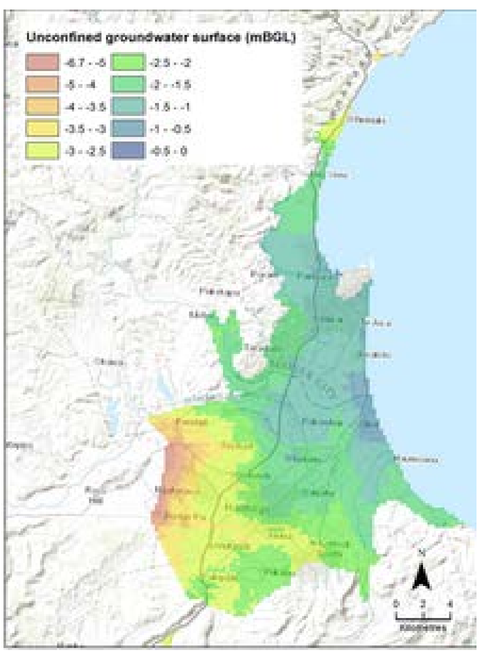
Where the density of CPT data is lower, the similarity in the CPT data with areas of higher CPT data density and similarities in the geomorphology and subsurface geology have been used to determine the liquefaction response to earthquake shaking. In areas where CPT data is lacking altogether the geomorphology and subsurface geology have been used to assess the liquefaction response.

Each polygon in the spatial data (from the geomorphic map) used to differentiate the liquefaction susceptibility was assigned a data quality assignation of high, moderate or low confidence depending on the density of the available CPT data.

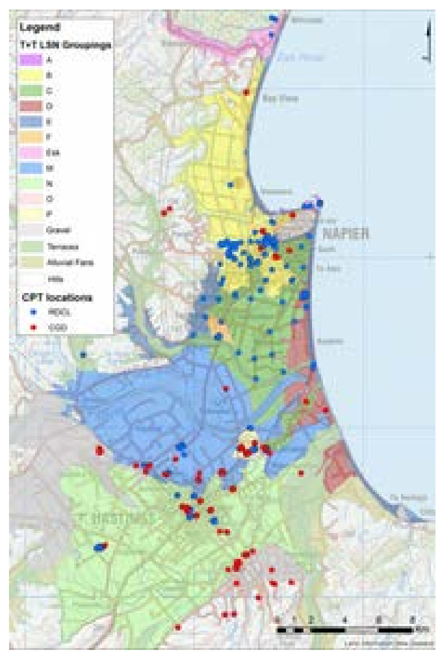


a) Geomorphological map of the Heretaunga Plains

b) Sediments potentially susceptible to liquefaction



c) Unconfined groundwater surface depth



d) Liquefaction Zones: (Note: dots are CPT locations)

Figure 1 Liquefaction Severity Number (LSN) input parameters

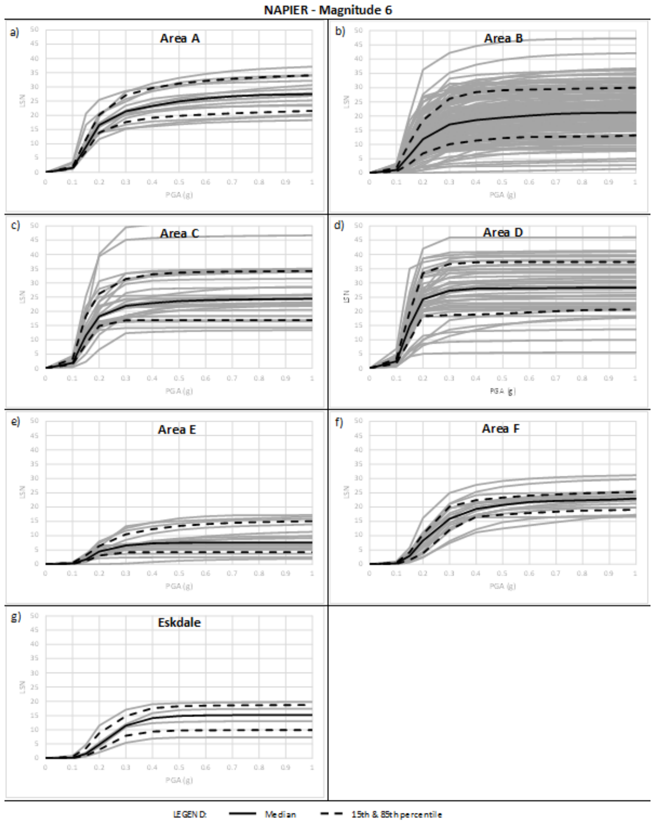


Figure 2 LSN vs PGA curves Mag 6 earthquake

(Note: 1. Areas refer to Liquefaction Zone boundaries from Figure 1D
2. Similar plots computed for Magnitudes of Mw= 5, 6, 7, 8)

4.2 Liquefaction Vulnerability

The liquefaction vulnerability functions were developed from experience derived from the Canterbury Earthquake sequence and the damage to buildings and infrastructure observed following those events. The damage has been classified according to the Differential Displacement Index (DDI) and the sub-floor construction types as prescribed in Table 2. Unfortunately the sub-floor (foundation) type is one least known attributes of most buildings and in many cases it has been assigned by statistical extrapolation from limited sample observations of similar locations based on building use and building age band. It was assumed that modern buildings (1980's +) of medium- or high-rise (i.e. 4 storey or more) form would have been subjected to sound geotechnical site investigation and have engineered foundations. Low-rise commercial/industrial buildings were assigned ‘light RC slab’ designation when built prior to 1990, and otherwise ‘enhanced RC slab. Residential buildings foundation types were developed from statistical extrapolation from field survey and assigned either ‘timber pile’ or ‘light RC slab’ according to age.

Damage and loss associated with lateral spreading are included in the model. Lateral spreading is the phenomenon where liquefaction occurs within one or more near surface soil layers and causes horizontal movement of upper soil layers relative to deeper soil layers. This usually only occurs where those soil layers susceptible to liquefaction extend to a natural depression (usually a watercourse).. The increased pore pressure results in both a loss of bearing capacity and a loss of shear capacity, which if it extends to the watercourse has the potential to generate a temporary slip layer which, in combination with gravity, results in the overlying landmass sliding towards the watercourse. Extension cracking within the mobilised landmass results at intermittent intervals across the mobilised block. Such cracks are highly destructive to buildings or systems which straddle them. The vulnerability function developed for lateral spreading is such that within Lateral Spread Zones, identified according to specified distances from water courses of different depth, one building in two will experience complete damage (Damage State 4) and experience complete loss when the liquefaction trigger value is exceeded and the LSN is >25, with 1 in 4 buildings likewise damaged for LSN in the 15 to 25 range (where the likelihood of forming a continuous slip surfaces at depth and less)

Table 2 Differential displacement index vulnerability/fragility enhancement factors

Differential Displacement Index (DDI)	LSN Range	Differential Displacement[1] (mm)	Incremental Damage and Repair Costs		
			Timber Piles, Perimeter Wall	Light RC Slab[3]	Enhanced RC Slab[2,4] or Deep Piles
DDI(0-)	N/A	0	Non-liquefiable area – no damage		
DDI(0)	0 ~ 5	< 10	Very low Liquefaction hazard – No Damage		
DDI(1)	5 ~ 15	10 ~ 25	Minimal Damage {DS+0 DR + 0.05}	Narrow Cracks epoxy fill repair {30% DS+1 DR+0.1}	Minimal Damage {DS+0 DR+0.1}
DDI(2)	15 ~ 25	25 ~ 50	Re-level Jack & Pack {30% DS+1 DR+0.12}	Slab Cracked – cut-out and epoxy repair {30% DS+1 DR+0.25}	Slab and Foundations OK – minor damage lower partitions and facades {DS+0 DR+0.15}
DDI(3)	25 ~ 35	50 ~ 100	Re-level Minor repair needed to linings and cladding {50% DS+1 DR+0.15}	Replace slab Repair needed to linings and cladding {50% DS+2 DR+0.4}	Re-Level likely Some Pile damage Minor repair needed to linings and cladding {DS+0 DR+0.3}
DDI(4)	> 35	>100	Re-level Repair to fitout {50% DS+1 DR+0.3}	Damage extensive Uneconomic to repair. {50% =DS4 DR=1}	Damage extensive Uneconomic to repair. {DS=0 DR=1}

Notes:

1. Differential displacement is assumed to be 50% of the total liquefaction-induced vertical displacement.
2. Commercial buildings of 3 storey or more are assumed to have piled foundations for normal settlement control and will not experience additional damage from liquefaction
3. ‘Conventional slab’ is a concrete slab as prescribed by NZS3604.
4. ‘Enhance slab’ is as prescribed by TC2 MBIE guidelines for Canterbury – being 300mm thick slab with reinforcing top and bottom or 400mm deep stiffener ribs wherein damage state remains as per shaking but damage ratio (cost) increases
5. Values in { } brackets indicate percent where additional damage from liquefaction limited to DS4 and additional Damage Ratio to be applied to DR1
6. Enhanced damage has been randomly applied to 30% of buildings with LSN < 25 and 50% of those LSN >25.

5 Exposure Modules

The exposure modules used for the study were enhanced from the standard RiskScape modules (derived from modified national rating records) supplemented by local building footprint and LiDAR aerial location data. Pipe network data was supplied by local Territorial Authorities and the power distribution network from the local lines company, Unison. Roading data was supplied from local roads administration agencies and the State Highway data from New Zealand Transport Agency. (Note at the time of writing, the roading data has been loaded in to the model but the lack of suitable vulnerability functions prevent it from being used for liquefaction loss projects at this time).

The regional population statistics were extracted from the New Zealand census data 2013 [15] with 90% of the population being assumed in their places of residence for night occupancy. Employment statistics were used to reallocate people into their daytime locations. However, the Hawkes Bay is largely an agricultural and horticultural region, and it has been problematic assigning people into rural and rural-industrial building occupancy spaces. People were also allocated to ‘transit’ conditions where they were considered outside buildings.

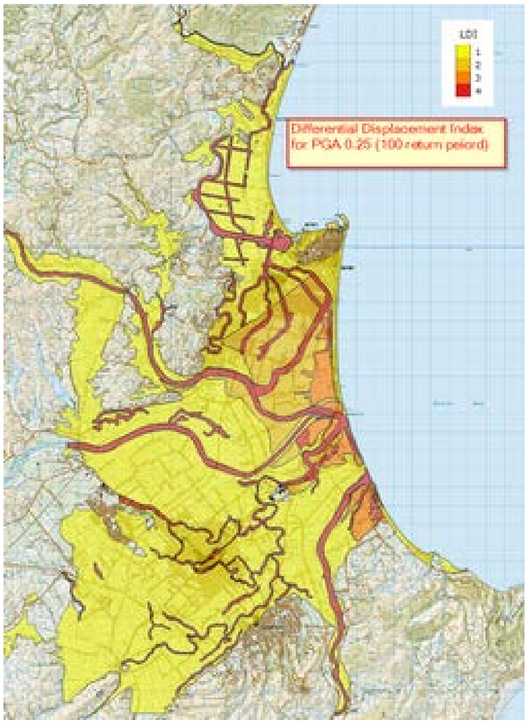
A grid of ‘virtual assets’ was used as the basis for evaluating the liquefaction ground deformation across the region. This was required since the liquefaction module derived results only apply at asset locations. The grid consisted of a 250m by 250m grid with a refined 10m x 10m grid applied around water ways (where lateral spreading evaluation was required). This virtual grid enabled the creation of the Differential Displacement Index maps which are expected to underpin decisions around regulatory intervention and planning policies.

6 Results and Applications

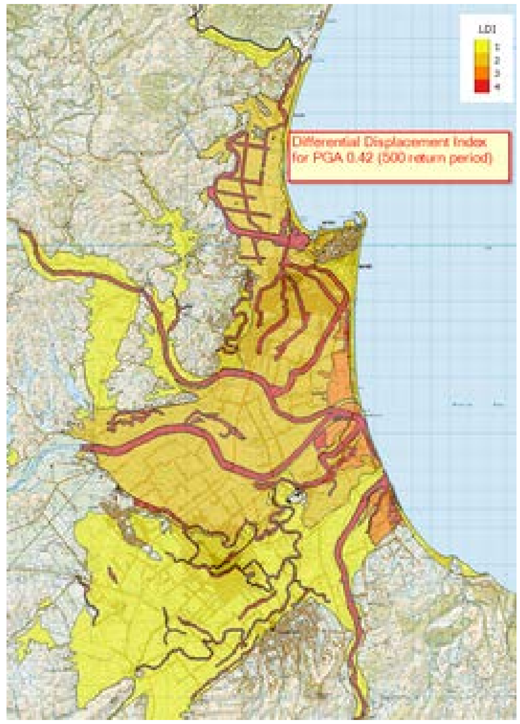
The results from the study are included as modules (plugins)within the RiskScape tool which has both the enhanced exposure data derived for the region and the Liquefaction Module embedded within it. RiskScape tool has been developed to enable users with different skills and needs to interface with the model and generate results in various forms to suit their particular requirements. Results can be presented in 2-D as a map image of aggregated losses, as a 3-D stack of damage results using a Google Earth interface, or as a csv file for external (Excel or otherwise) statistical or financial evaluations. Scenarios available within the programme are stored and can be readily retrieved for comparison with alternative decisions. By using the filter function within RiskScape it is possible to filter assets according to user-driven preferences, for instance evaluate public buildings or critical facilities (including their geographic spread, thereby enhancing planning post disaster response by identifying neighbourhoods where greater damage is expected or local access may be more greatly inhibited).

The needs for each of the three identified User Sectors were recognised and considered as follows:

1) **UserSector1:** Building official and planning consent officers: the grid of ‘virtual assets’ was used to determine the maps of Differential Displacement Index for each return period being considered. In deriving these maps, the target PGA value was applied at all asset locations within the three regions being considered and maps showing DDI produced. Two such maps are shown in Figure 3 below. It is expected that recurrence interval will be set, expected to be around 100 year return period below which damage will be deemed intolerable. Since this sector is involved in consents and permits prior to development, it can initiate damage mitigation countermeasures if the generalised model assumptions are verified by site specific geotechnical investigation. Such countermeasure may involve the use of piles or enhanced foundation systems either robust enough to avoid damage and/or capable of being re-levelled should liquefaction be experienced.
2) **UserSector2:** Recovery and response sector where event-recurrence-interval-based scenario evaluations particularly of housing damage to Damage State 3 or above (i.e. unsuitable for continued occupancy although may be repairable (DS3) or may be uneconomic to repair (DS4) or complete (DS5)) where the need and geographic spread of post-event shelter needs can be assessed. The Territorial Authority responsibility for ongoing community function following an event is also expected to be informed by considering damage disruption to community facilities and lifeline utilities together with people and business dislocation. Results such as those quantifying one realisation from each recurrence interval suite are shown in columns 4 and 5 of Table 4.
3) **UserSector3:** Insurance and financial risk transfer sector where event-recurrence-interval-based scenario evaluations particularly of direct losses and economic impact was of paramount interest. The user interface enables both the selection of specific sets of events to be considered. The results of direct economic loss of one realisation from each recurrence interval suite are provided in columns 2 and 3 of Table 3 with the enhanced loss projection gained by directly considering liquefaction damage being the cost difference between these two sets of values. This data is also presented in Figure 4



A) DDI PGA=0.25 (100 yr return period)



B) DDI PGA=0.42 (500 yr return period)

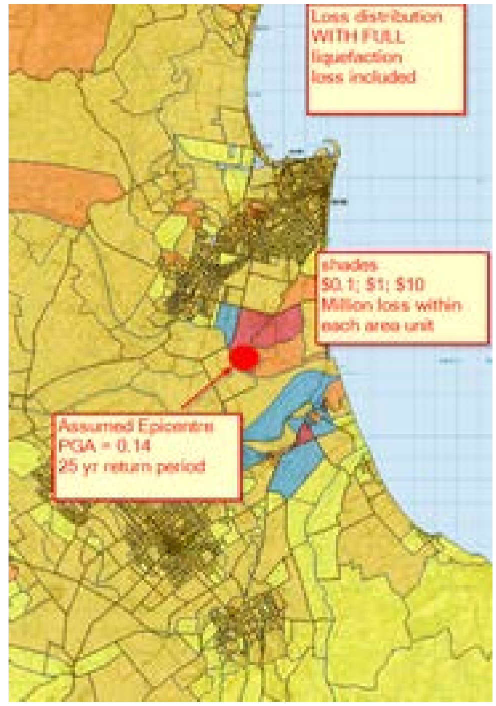
Figure 3: Differential Displacement Index Maps

(Note: Where DDI=1 are not expected to experience damage – no intervention required
DDI=2 damage to light slabs but timber and enhanced slabs OK – detailed geotech investigate if light slab construction is proposed otherwise OK
DDI=3 Detailed Geotech investigation and specific foundation design expected
DDI=4 Detailed Geotech investigation, specific foundation design or mitigate by avoidance.)

Table 3 Loss projection for one realisation of each suite of motions

Return Period (years)	Target PGA (g)	Repair Costs ($M)		People displaced (number *1000)
		Shaking only	Shaking + Liquefaction	Shaking + Liquefaction
25	0.14	<5	<5	0
100	0.25	26	60	0.2
500	0.42	850	2,550	6.9
1000	0.51	7,190	9,460	21.3
2500	0.64	34,060	34,268	27.4

A) Shaking Only - M$ loss per unit area



B) Liquefaction and shaking $M loss/unit area

Figure 4: Typical loss distribution map with and without liquefaction being specifically modelled.

7. Conclusions

The creation of a Liquefaction Module with a sound geotechnical basis is possible and justified even when the input data is sparse and its resolution is low. Such a model has been developed and is included in a prototype version of the RiskScape Regional Risk tool being used in New Zealand. When linked to the risk-based derivatives of the National Seismic Hazard model the tool provides a rational basis for determining the impact of liquefaction both in regards direct losses and damage potential. The development of the required link between shaking severity and return period within the tool has the potential to underpin critical planning and building consent requirements across the region. The model is capable of delivering damage and loss maps across the region for the various return periods nominated. The reliability of these loss projections remains of concern since the base geotechnical data upon which the projections are based is ‘sparse’ in some areas.

Liquefaction related losses to buildings within areas of moderate to high liquefaction susceptibility are expected to be significant and should therefore be included in any loss modelling. Mitigation measure such as enhanced foundations or land-use planning avoidance are effective countermeasures from such damage, but need to be applied prudently and appropriately to avoid undue up-front expense during construction.

The liquefaction susceptibility of any particular site does not have a unique solution since it is dependent on many variables, some of which are seasonal (water table depth), some site specific (density and composition of the near-surface soil conditions) and some event dependent (the shaking intensity at any specific site, the magnitude of the triggering event and the source to site distance). While some sites can be identified as non-liquefiable (gravels and hill sites), others on alluvial planes have the potential, when subjected to sufficient and prolonged shaking, to exhibit liquefaction characteristics.

A risk-based approach is therefore appropriate to screen those sites where liquefaction is sufficiently unlikely (and should be ignored) for others where the potential is sufficient to merit either intervention or avoidance.

4. Acknowledgements

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