REGIONAL ASSESSMENT OF LIQUEFACTION VULNERABILITY IN MARLBOROUGH, NEW ZEALAND

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Abstract

Major earthquake events worldwide have highlighted the impact of soil liquefaction on the built environment. A good understanding of the areas where liquefaction damage is possible is important for informed land-use planning and to allow developers and asset owners to appropriately address the risk. In this research regional assessment of liquefaction vulnerability for the Lower Wairau Plains in the Marlborough region of New Zealand is undertaken. Alluvial deposits of fine-grained silts and sands combined with low-lying topography suggest the presence of liquefiable deposits over significant portions of the region, and manifestations of liquefaction were observed in the past earthquakes, including the 1848 Marlborough and 1855 Wairarapa earthquakes, and more recently during the 2013 Lake Grassmere and 2016 Kaikōura earthquakes. This paper discusses the detailed methodology adopted for this assessment with description of different levels of liquefaction vulnerability assessment and preliminary findings from each level. It includes qualitative screening using surface geological maps, screening using seismic design inputs and regional groundwater models, and screening based on the geomorphology present in the region. A detailed basin geological model developed for groundwater modelling was used to define the thickness of the surface gravel crust over the alluvial deposits. The most detailed level of analysis groups CPT investigations together in common geomorphic zones in order to provide an indication of the representative performance of the different soil and depositional settings. The liquefaction severity number (LSN) was used to estimate the surface manifestation severity and how it varied in each zone over a range of design earthquake intensity levels. With these multiple approaches, regional liquefaction-induced ground damage maps are developed for the Lower Wairau Plains for different levels of investigation detail.

Keywords: Liquefaction, earthquake, cone penetration test, mapping, liquefaction-induced damage

1. Introduction

Liquefaction is a common cause of ground failure during earthquakes and is directly responsible for significant damage to civil infrastructure. Manifestations of liquefaction include the occurrence of sand boils and lateral spread failures, settlement and tilting of structures, cracking of pavements, and failure of buried lifelines [1,2]. Earthquake-induced liquefaction phenomena have been recorded in many parts of the world including the 1990 Luzon earthquake in Philippines [3], the 1995 Kobe earthquake in Japan [4], the 1999 Kocaeli earthquake in Turkey [5], the 1999 Chi-Chi earthquake in Taiwan [6] and most recently the 2011 Van earthquake in Turkey [7], the 2011 Christchurch earthquake in New Zealand [8], the 2011 Tohoku earthquake in Japan [9] and 2016 Kaikōura earthquake in New Zealand [10,11,12].

This paper summarises the regional liquefaction vulnerability assessment of the Lower Wairau Plains in Marlborough, New Zealand. The primary objective of this research is the identification of the likely spatial distribution of the liquefaction vulnerability of the land. The Lower Wairau Plains are located in the north-east of the South Island of New Zealand in the region of Marlborough. Figure 1 shows the geographic location of the Lower Wairau Plains. A number of historic earthquakes; the 1848 Marlborough and 1855 Wairarapa earthquakes, and more recently the 2013 Lake Grassmere and 2016 Kaikōura earthquakes have produced varying modes of liquefaction manifestation in the region [12]. Therefore, the primary objective of this assessment is the identification of the spatial distribution of the liquefaction vulnerability in the region The scope of work presented in this paper comprises the collation of all available data within the study area to inform a liquefaction vulnerability assessment based on the document "Planning and engineering guidance for potentially liquefaction-prone land" [13]. This is referred to as the MBIE Guidance throughout the remainder of this paper. Geological, groundwater and seismic hazard data were used to undertake a high-level assessment. Geomorphological and basin groundwater geological models were used to further refine this high-level assessment. A cone penetration test (CPT) dataset was used with the seismic hazard and groundwater data to provide an assessment of the liquefaction hazard for a range of earthquake shaking return period scenarios. CPT investigations in each geomorphic zone were grouped together to provide an indication of representative performance of the soils in these areas. The output of this research also includes a suite of maps of liquefaction vulnerability categories for the study area.

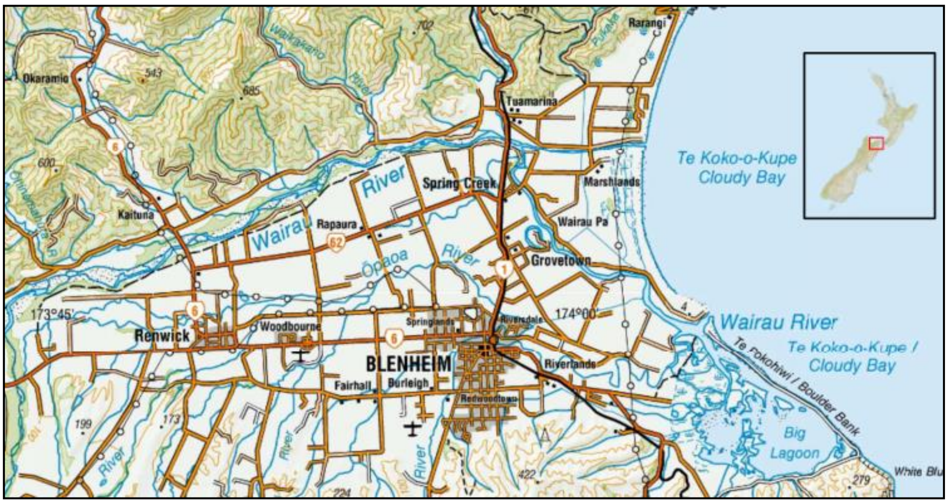

Figure 1: Geographic location of the Lower Wairau Plains, Marlborough, New Zealand

2. Methodology

In order to develop liquefaction vulnerability categories for the Lower Wairau Plains, the methodology presented in the MBIE guidelines "Planning and engineering guidance for potentially liquefaction-prone land", which is summarised in Figure 2, was applied.

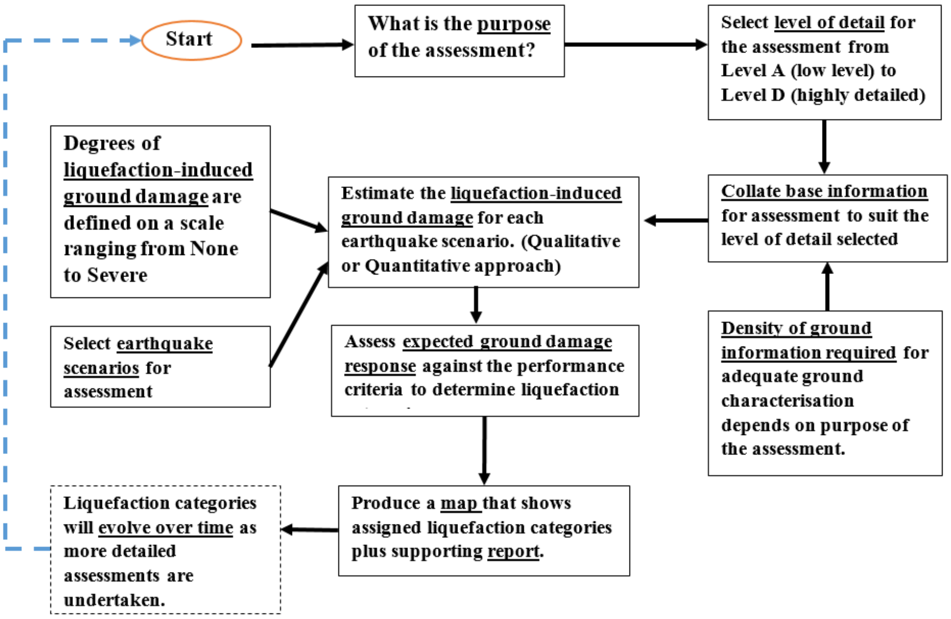

Figure 2: Overview of the recommended process for categorising the potential for liquefaction-induced ground damage [13]

The first step in this methodology was the definition of the level of detail for the assessment so that the required level of data and resources can be defined. Three levels of assessment are employed in this research: Level A, B and C. Level A is a basic desktop assessment, Level B is a calibrated desktop assessment and Level C is a detailed region-wide assessment. The liquefaction vulnerability categories assigned in each level of assessment are summarised in Figure 3. As the level of available information increases, the precision of categorisation can increase. The default vulnerability category is “Liquefaction Category is Undetermined”. This is assigned to areas where a liquefaction assessment has yet to be undertaken, or if there is not enough information to define an appropriate category. Two categories, “Liquefaction damage is possible” and “Liquefaction damage is unlikely”, are used in Level A and B assessments and more precise categories of “Very Low”, “Low”, “Medium” and “High” can be applied after Level C detailed assessment.

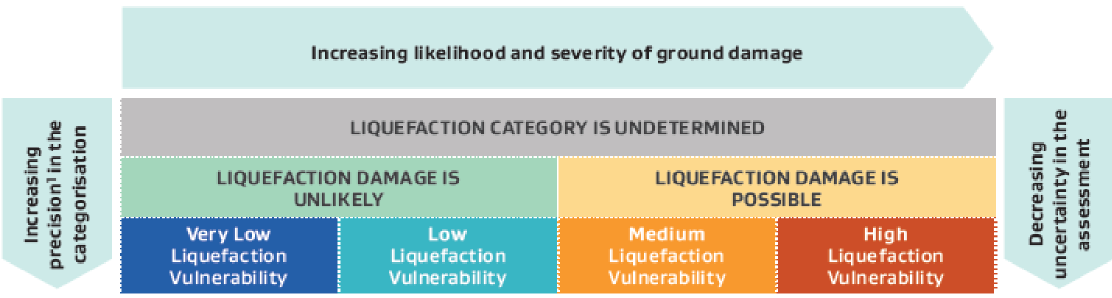

Figure 3: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform the planning and consenting process [13]

2.1 Level A Assessment

Level A is a basic desktop study that utilises surface geology, groundwater and design ground motion characteristics to classify the liquefaction potential. One of the primary focuses of this assessment is to differentiate between the land where “liquefaction damage is unlikely” and ‘liquefaction damage is possible’. Potentially liquefiable deposits are defined based on the classification by Youd & Perkins (1978) and other researchers [14,15,16]. This geology-based classification considers the regional design ground motions and the depth to groundwater in conjunction with the age and depositional processes that formed the soil deposits. A semi-quantitative screening criterion, illustrated in Table 1, is used to identify geological units where liquefaction-induced ground damage is unlikely to occur. A soil deposit of the specified type may be assigned a liquefaction vulnerability category of "Liquefaction damage is unlikely" if the 500-year return period peak ground acceleration (PGA) is less than the value listed, or if the depth to groundwater is greater than the value listed.

Table 1: Semi-quantitative screening criteria for identifying land where liquefaction-induced ground damage is unlikely [13]

Type of soil deposits	A liquefaction vulnerability category of "Liquefaction damage is unlikely" can be assigned if either of these conditions is met:	
	PGA for the 500-year intensity of earthquake shaking	**Depth to groundwater**
Late Holocene age	< 0.1 g	> 8 m
Holocene age Less than 11,000 years old	< 0.3 g	> 6 m
Latest Pleistocene age Between 11,000 and 15,000 years old	< 0.3 g	> 4 m

2.2 Level B Assessment

The Level B assessment is a calibrated desktop assessment, where the details from the Level A assessment are further refined using additional datasets that can further clarify the subsurface characteristics and land performance. Qualitative assessment using simple screening criteria based on geomorphology can identify areas where there is potential for liquefaction induced ground damage to occur, or the landform suggests it may have occurred in the past can inform the calibration the liquefaction vulnerability categories. Any other regional information on subsurface deposits can be fed into this calibrated assessment, such as lithology from 3D groundwater models.

2.3 Level C Assessment

The Level C assessment is a detailed area-wide assessment based on cone penetration test (CPT) soundings and applies a quantitative approach. These CPT soundings from across the region are used to estimate the degree of liquefaction-induced ground damage for a range of peak ground accelerations and earthquake magnitudes that are representative of the seismic hazard across the region. CPT data, the return period events, and the groundwater data discussed are used as input into the Boulanger and Idriss (2014) [17] simplified liquefaction triggering methodology to assess where liquefaction is expected to occur within the soil profile. This triggering methodology was used in conjunction with the Liquefaction Severity Number (LSN) to estimate the severity of liquefaction-induced land damage [18].

3. Ground conditions and Seismicity

3.1 Geology

The Lower Wairau Plains are located in the northeast of the South Island of New Zealand in the region of Marlborough. The Lower Wairau Plains are predominantly flat to gently undulating alluvial plains, underlain by Holocene age marine and estuarine silts and sands of the Dillons Point Formation, and alluvial gravels and sands of the Rapaura Formation. The soils of the Dillons Point Formation are observed to vary significantly in their composition and degree of consolidation, varying between loose sands and soft silts to very dense sands and very dense clayey silts [19]. The alluvial sediments to the eastern margin of the Wairau Plains are inter-fingered with lagoonal muds and coastal sands, silts, and gravels which reflect coastline progradation and marine regression following the mid-Holocene high stand 6,000 years ago [20]. Figure 4 summarises the simplified surface geological deposits present in the Lower Wairua Plains.

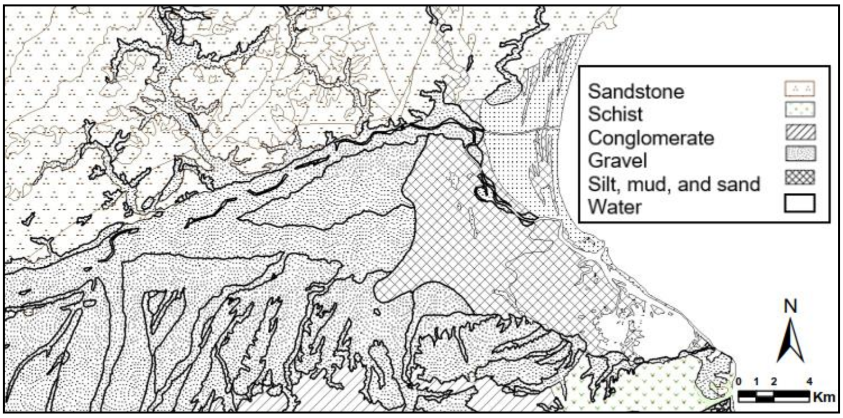

Figure 4: Geologic map of the Marlborough Region [21]

3.2 Geomorphology

The geomorphology of the coastal portion of the Lower Wairau Plains was mapped by Bastin et al [22] as part of the wider study assessing the geomorphological influences on liquefaction following the 2016 Kaikōura earthquake. The morphology of the Lower Wairau and Opaoa Rivers is meandering and is characterised by a single sinuous channel that forms meaner bends. During bank full conditions, high velocities are concentrated towards the outer banks and deflect the flow towards the adjacent inner banks causing the eroded material to deposit, which is generally fine sand grading to silt termed as point bar deposits. As the river overtops its banks, fine sand to silt material is deposited on the surrounding alluvial plain. Swamp areas where standing water remains following flood events are generally formed in areas distal to the river. Topographic depressions filled with channelised fine to medium sands are present in the landscape indicating the abandoned river channels, termed paleochannels. The geomorphic map for the lower portion of Wairua Plains is presented in Figure 5.

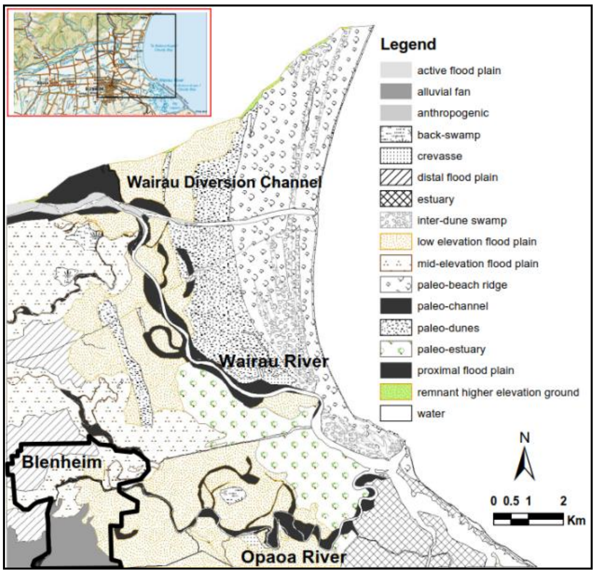

Figure 5: Geomorphic map of the coastal portion of the Lower Wairau Plains [22]

3.3 Groundwater

The study of Davidson & Wilson [23] provides a thorough description of the groundwater regime of the Lower Wairau Plains. Similarly, the groundwater model developed by Ogden [24] indicates that groundwater depth was approximately 2 m below ground level for much of the coastal parts of the plains and flows from west to east. Figure 6 illustrates the median groundwater depths from the available groundwater information for the region and the depositional age of the deposits. The depth increments used in this figure are aligned with the depth limits used in the semi-quantitative screening criteria in Table 1, where deposits of different depositional ages can be assigned a liquefaction vulnerability category of "liquefaction damage is unlikely".

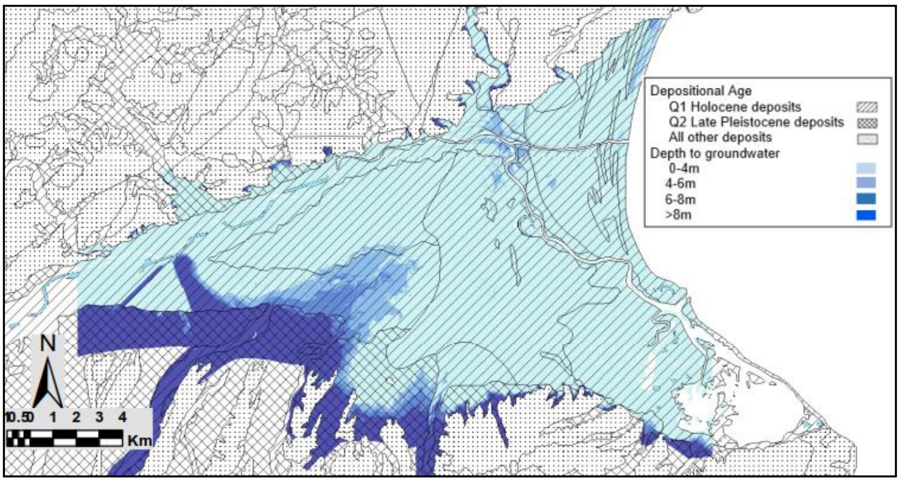

Figure 6: Depositional age of deposits and median groundwater depths for the Lower Wairau Plains

3.4 Seismic Hazard

The plate boundary between the Pacific and Australian plates passes through the Marlborough region, and consequently, this region is an area of high seismicity. The Marlborough region consists of a series of northwest-tilted blocks forming mountain ranges, hills and drowned valleys separated by major translucent faults such as Wairau, Awatere and Clarence Faults, each of which can give rise to frequent seismic events [24]. For the liquefaction assessment, peak ground acceleration (PGA) and earthquake magnitude for the Lower Wairau Plains were defined following the New Zealand Transport Agency Bridge Manual SP/M/022 [25]. A site subsoil class of D is used across the region, due to the presence of deep deposits. The design PGA for the Lower Wairau Plains is 0.21g for a 100-year return period and 0.43g for a 500-year return period. The earthquake moment magnitude for each return period was M_w 6.1 and M_w 6.75, respectively.

4. Results and Discussions

This section presents the preliminary results of the different levels of the liquefaction vulnerability assessment undertaken in this research.

4.1 Basic Desktop Assessment

Q-Maps developed by GNS Science were used to create geological layers for the Lower Wairau Plains. In general terms, the basement, Late Pliocene, and Early Pleistocene rocks are lithified or relatively well consolidated and will not liquefy under strong ground shaking. Because of their age, the early and middle Pleistocene non-marine and marine deposits, the last interglacial marine deposits, and the alluvial materials of the early and middle last glaciation are old enough to have been consolidated by natural processes. Their liquefaction susceptibility is regarded as negligible [14]. Therefore, the Pleistocene deposits with groundwater deeper than 4 m could be categorises separately using the semi-quantitative criteria presented in Table 1. Substantial uncertainty remains regarding subsurface conditions elsewhere, but the geological maps show that alluvial deposits of fine-grained silts and sands are present. These alluvial deposits are inter-fingered with mud, sands, silts and gravels. Liquefaction induced ground damage could be possible in these deposits where depth to the ground water table is within limits presented in Table 1. Most gravelly soils are relatively well-drained and there is no increase in pore pressure, but drainage can be impeded if their voids are filled with finer particles or they are surrounded by less pervious soils. The level of detail of the surface geological maps is not sufficient to differentiate this in gravel dominated alluvial deposits. Therefore, at this level of assessment, it is considered that liquefaction damage could be possible in "gravel" deposits on the Plains that are of Holocene age. Based on the above discussion, Figure 7 shows the location of rocks and young and old alluvial deposits with varying values of depth to groundwater following the semi-quantitative criteria presented in Table 1.

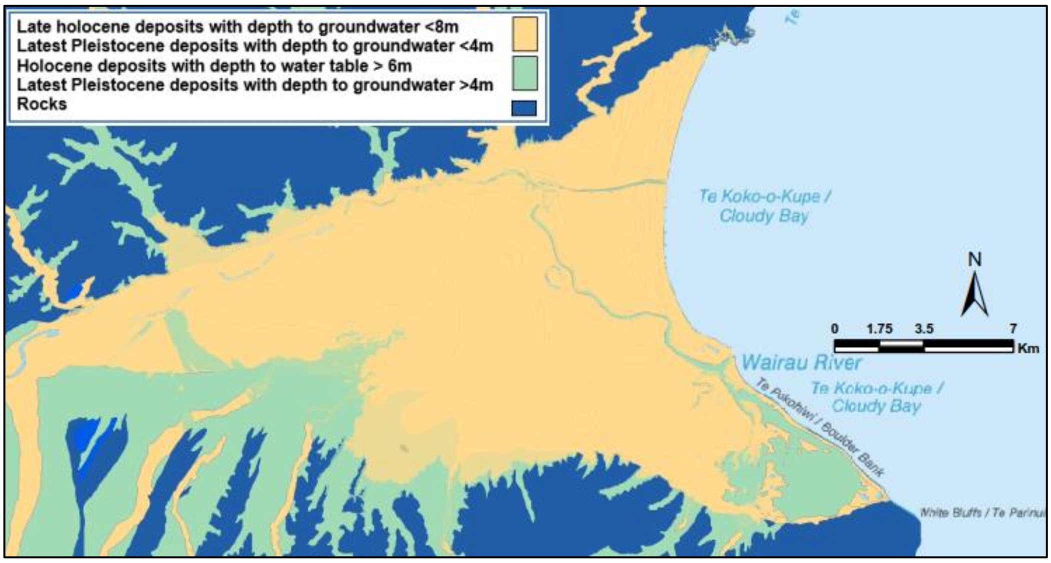

Figure 7: Geology-based liquefaction vulnerability category map for the Lower Wairau Plain

4.2 Geomorphic and Stratigraphic Assessment

4.2.1 Geomorphology-based screening

The geomorphology of the Lower Wairau Plains discussed in Section 3.2 is assessed in this section in conjunction with the potential for liquefaction manifestation using literature related to the performance of typical geomorphological formations in recent earthquakes.

The limited deposition on the outer bank and predominance of silts in the distal floodplain result in lower liquefaction susceptibilities of the underlying sediments. Point bar deposits comprised of fine-grained sand grading to silt. These deposits are geologically young, unconsolidated and saturated, and thus are likely to liquefy during future events. Interdune swamp deposits in the Lower Wairau Plains are composed of mainly silts with layers of peat and mud. Crevasse along with point bar deposits being late Holocene deposits (age <3500 yrs old), unconsolidated and saturated did not perform well in historic earthquake events and have a high liquefaction potential. Estuary deposits from the mainland to estuary in the northeast towards shoreline and lagoon are silty and gravelly in nature and have high liquefaction potential. Paleo ridge formations are composed of sand as well as sediment worked from underlying beach material. South of the Wairau River there is a single gravel ridge (the Boulder Bank) which forms a spit enclosing the Wairau Lagoons. Dune formations towards the shore are also dominated by gravel deposits. Similarly, gravel beach ridges are present from the modern coastline to 5.5 km inland, whereas discontinuous sand dunes are present from 5.5 to 7 km inland. Generally, these deposits have low liquefaction potential considering gravel dominated material and depositional characteristics, as these are compacted by wave action. Based on the available geomorphological data, different zones can be described as *less susceptible* and *more susceptible*. This can be used to inform further site investigation to refine classifications based on increased density of site investigation data. Figure 8 summarises these characteristics for the eastern part of the Wairau Plains.

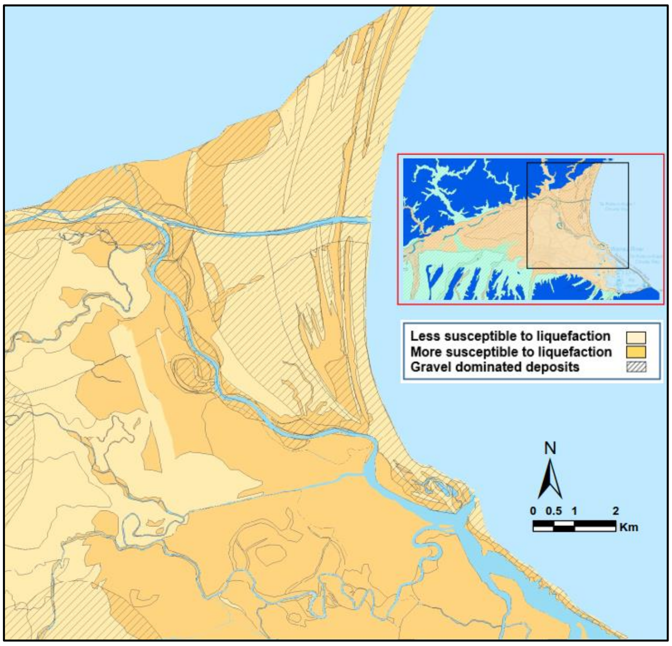

Figure 8: Summary of the susceptibility of different geomorphological zones in the Wairau Plains

4.2.2 Detailed basin geological model

White et al. (2016) [26] developed a detailed geologic model of the basin beneath the Wairau Plains to better understand groundwater-surface interactions. Observations of lithology from 1,165 wells were used to develop a continuous 3D distribution of de-facto probabilities for the occurrence of three sediment classes: gravel, sands and clays. Across the Wairau Plains at the locations shown in Figure 9, cross-sections from the model were extracted to a depth of 20 m, with depths greater than this of less importance for liquefaction assessments.

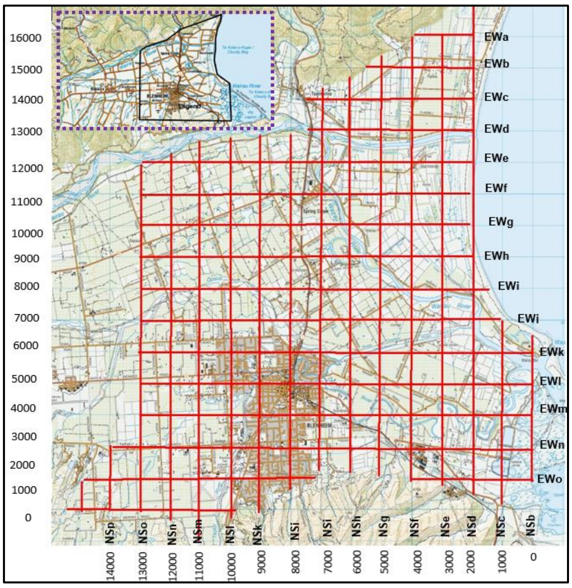

Figure 9: Location of basin model cross-sections in the east-west and north-south directions

A number of north-south and east-west cross-sections were extracted and an example of cross-section in north-south direction is shown in Figure 10. This figure shows the 80% probability of occurrence of gravel and the depth to groundwater from the model presented in Figure 6. As the water table was within a gravel layer towards north, the depth was set to the base of the gravel deposits at that location and as there is no gravel on southern side of cross section, thickness of surface gravel deposits was set to zero.

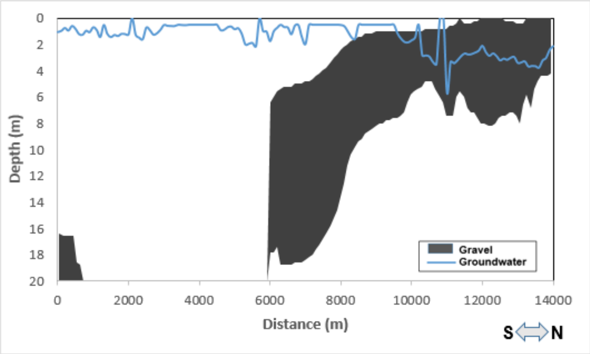

Figure 10: Location of gravel deposits and groundwater depths for cross-section NSm.

The main focus of this study was to differentiate between locations where gravels would dominate the potential surface manifestation severity and those where sands would dominate. To achieve this, the thickness of the gravel crust was defined across the plains. Effects of near-surface non-liquefying deposits against the surface manifestation of liquefaction is well documented and observations from historic events have indicated a minimum crust thickness of 5 m could prevent the surface manifestation of liquefaction [3]. The resulting surface after the analysis of all cross-sections is present in Figure 11, showing that the depth to the base of the surface gravels is greater than 5 m in the areas west and south of Blenheim, as well as along the coast to the north-east.

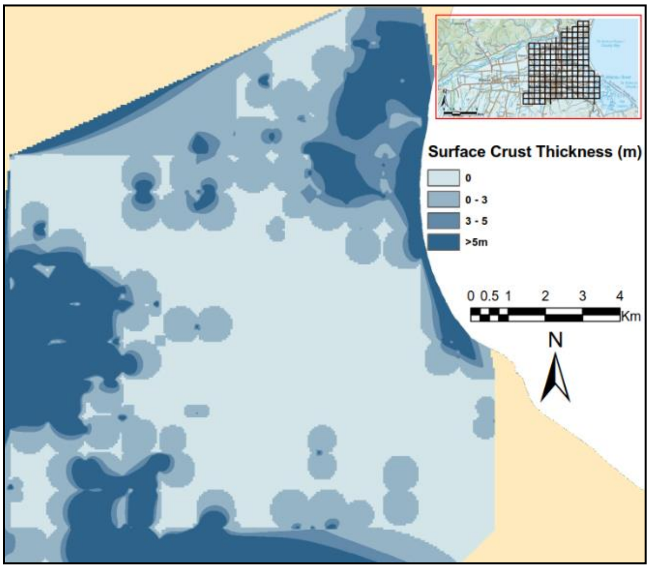

Figure 11: Summary of the detailed geologic basin model analysis showing the depth of the base of surface gravels.

4.3 CPT-based assessment

The analysis of CPT soundings in the region is used to undertake an estimate of the degree of liquefaction-induced ground damage for various earthquake scenarios. CPTs are available in six geomorphic groups in the Lower Wairau Plains and these are grouped together. Characteristic LSN values are adopted for the purpose of the study are presented in Table 3 and the LSN values are overlaid on the geomorphic formations in Figure 12 using the colour scheme from Table 5 to highlight the degree of damage. The analysis shows that the degree of damage in the formations of proximal flood plains, low elevation flood plains, point bar and paleochannels are in the range of “Moderate to severe”. Similarly, CPT analysis in areas with alluvial fans and mid-elevation flood plains formations have a “None to minor” degree of damage in most scenarios. There is no CPT data available in the rest of the study area and it is recommended that more geotechnical investigations be carried out to refine the liquefaction vulnerability categories.

Table 3: Characteristic LSN ranges adopted for the purpose of the study [24]

Degree of liquefaction-induced ground damage	Approximate characteristics LSN ranges used for this high-level hazard study
None to minor	<13
Minor to moderate	13-18
Moderate to severe	>18
Note: These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).	

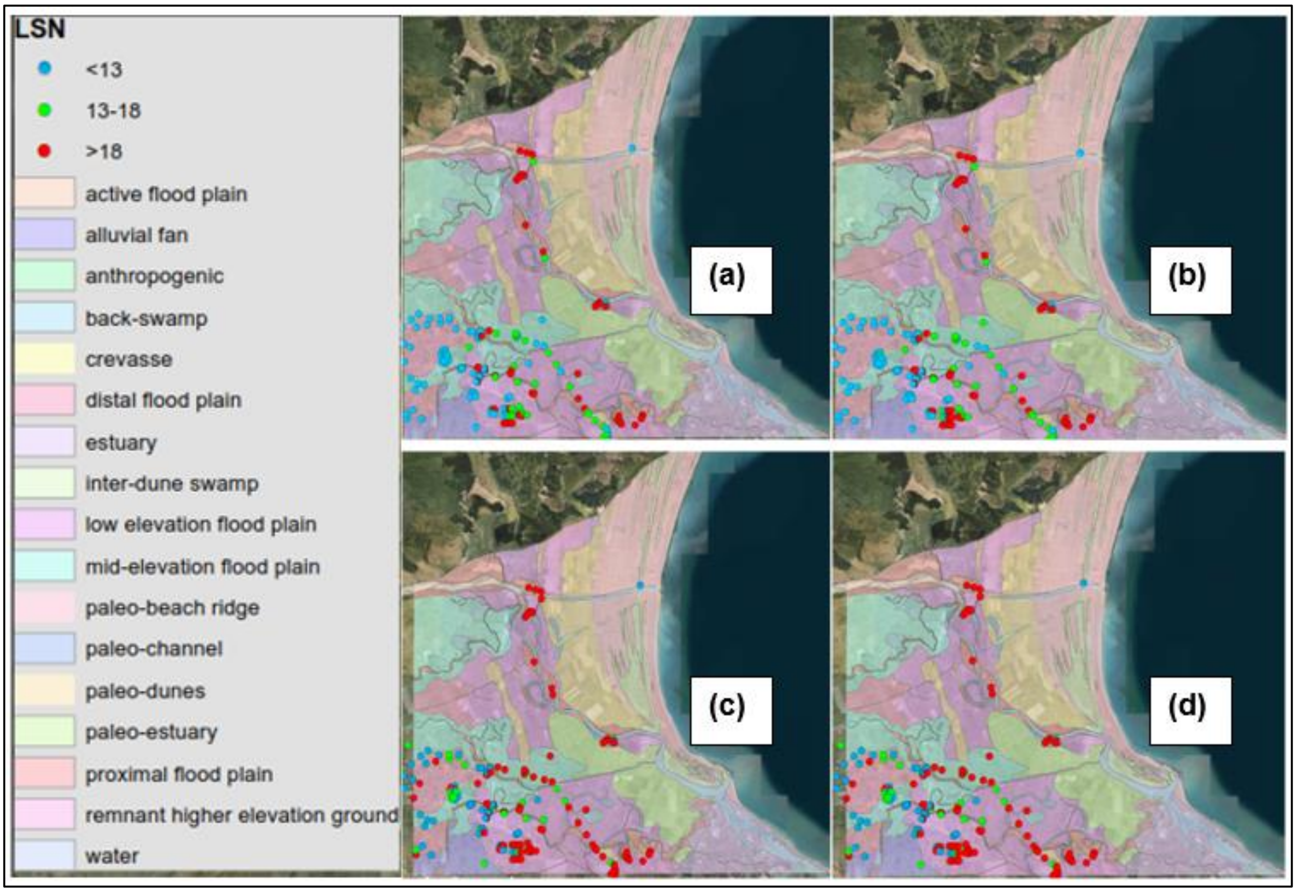

Figure 11-CPT analysis overlaid on geomorphic zones (a) M_w = 6.1, PGA= 0.21g (b) M_w = 6.75, PGA= 0.21g (c) M_w = 6.1, PGA= 0.43g (d) M_w = 6.75, PGA= 0.43g

5. Concluding Remarks

In this paper, an attempt has been made to assess liquefaction-induced ground damage for the Lower Wairau Plains in the Marlborough region of New Zealand using different levels of details. Three levels of assessment make use of extensive geological, geomorphological and geotechnical investigations data along with groundwater and seismic design inputs for the region. Preliminary results show that:

- Alluvial deposits of fine-grained silts and sands are present in the Lower Wairau Plains where liquefaction-induced ground damage could be possible. As surface geological-based assessment is unable to give clear demarcation of the alluvial deposits in the region, which are intermixed and have gravel domination in certain areas. Therefore, a more detailed geotechnical dataset plays a vital role in understanding the liquefaction vulnerability of gravel-dominated alluvial deposits in the region.
- Detailed study of geomorphological formations in the region shows that areas with low-level flood plains, proximal flood plains, paleochannel, point bar deposits, estuaries and interdune swamp deposits could be more susceptible to liquefaction-induced ground damage as compared to other formations in the regions, including distal flood plains, paleo ridges, alluvial fans and paleo dunes.
- Analysis of extensive datasets available from the detailed geologic basin model of the region had identified areas west and south of Blenheim where thick non-liquefiable gravel crust is present, while some areas to the north and northwest have surface gravel layer less than 5 m. The thickness of the gravel crust at the site crust may affect its liquefaction susceptibility.
- Initial results from Level C assessment provide a more detailed indication of the performance of some geomorphological formation where CPT soundings are available.

This research provides an initial indication of the liquefaction vulnerability of soil deposits across the region and shows the importance of geomorphological and geological dataset resolution for the liquefaction assessment in the region. Further refinement in level A and B assessments, detailed work using quantitative criteria in level C assessment and evaluating the estimates of liquefaction vulnerability categories to 2016 Kaikōura Earthquake observations is under progress. Maps developed associated with each level of assessment will benefit planners, asset owners, emergency managers, and engineers in assessing the vulnerability of their projects and assets with respect to the liquefaction of soil in the region.

6. Acknowledgments

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