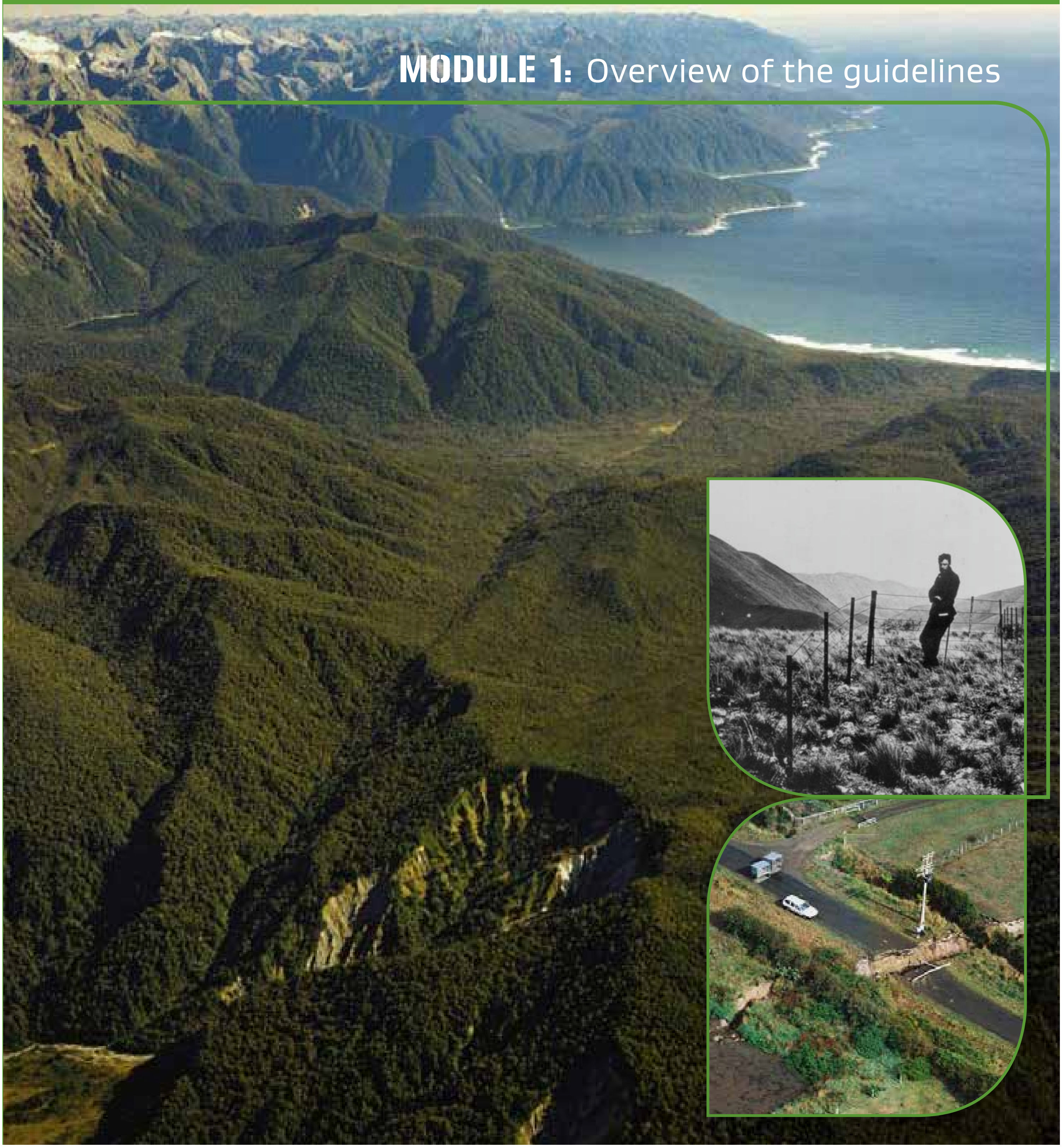
Earthquake geotechnical engineering practice

MODULE 1: Overview of the guidelines



MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
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NEW ZEALAND GEOTECHNICAL SOCIETY INC
www.nzgs.org

Acknowledgements

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- Dr Kevin McManus – McManus Geotech Ltd (lead author)
- Charlie Price – MWH Global, (NZGS Chair)
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- Mike Stannard – Ministry of Business, Innovation and Employment (MBIE)
- Nick Traylen – Geotech Consulting Ltd, MBIE's Engineering Advisory Group
- Rick Wentz – Wentz Pacific Ltd

EQC

- Particularly Hugh Cowan, Richard Smith

NZGS Management

- Particularly Gavin Alexander, Beca; Kevin Anderson, AECOM

Document Status

ISBN 978-0-947497-29-3 (print)
ISBN 978-0-947497-51-4 (online)

New Zealand Geotechnical Society (NZGS) and Ministry of Business Innovation & Employment (MBIE) guidelines for Earthquake Geotechnical Practice in New Zealand.

Rev 0

Issue Date March 2016

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Important Notice

This document is preliminary and the contents should be treated as draft guidelines. Submissions by the geotechnical community to the Society are encouraged, after which a further review will be undertaken. The contents may be subject to further changes, additions, and deletions.

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PREFACE

These guidelines for *Earthquake Geotechnical Engineering Practice* in New Zealand were originated by a working group of the New Zealand Geotechnical Society. The idea for the working group came from a panel discussion 'Geotechnical Seismic Design Standards' which took place during the NZGS Biennial Symposium 'Earthquakes and Urban Development' held in Nelson from 17–18 February 2006.

The main impetus for the panel discussion was the replacement of NZS 4203:1992 *Standard for General Structural Design and Design Loading for Buildings*, by NZS 1170.5:2004 *Structural Design Actions Part 5: Earthquake actions – New Zealand*. While far from complete, NZS 4203 gave some useful guidance to geotechnical practitioners. However, NZS 1170.5 specifically excludes design of soil retaining structures and civil structures including dams and bunds, the effects of slope instability, and soil liquefaction.

Even with the very limited guidance given in NZS 4203, there was perceived to be a significant and undesirable variability within earthquake geotechnical engineering practice in New Zealand. Ad hoc attempts were being made by individuals and organisations to interpret NZS 1170.5 for geotechnical design in ways that were perhaps never intended by the authors of that standard.

The meeting also strongly endorsed the view that 'guidelines' are far more desirable than 'codes' or 'standards' in this area. Flexibility in approach was considered a key part of geotechnical engineering with the technology in this area rapidly advancing.

Financial support for this early initiative was provided by the Department of Building and Housing (now the Ministry of Business, Innovation, and Employment, MBIE).

The first module of the guidelines (formerly *Module 1: Guideline for the identification, assessment, and mitigation of liquefaction hazards*) was published in July 2010 shortly before the Darfield earthquake of September 2010 and was well received and timely, considering subsequent events. It proved very useful in guiding practice during a period when a very large number of liquefaction site assessments were carried out following the Christchurch earthquakes and resulting widespread liquefaction.

It was always the intention of the Society that additional modules would be prepared on topics including foundations, retaining walls, and landslides. The impetus for these additional modules gained significant additional momentum as a result of the Canterbury earthquakes.

As a result of the Canterbury earthquakes, the New Zealand Government established the Canterbury Earthquakes Royal Commission (CERC) to consider the adequacy of current legal and best practice requirements for the design, construction, and maintenance of buildings in the context of earthquake risk. Seven volumes of reports were published with 189 recommendations. Of these recommendations, 175 sit with MBIE to execute with about 20 percent relating to geotechnical issues.

The CERC reports resulted in a large and critically important work programme for MBIE requiring the development of more formal links with the engineering community. In 2014 MBIE signed a *Memorandum of Understanding* with the New Zealand Geotechnical Society to better align and create a shared understanding of each organisation's objectives. It was also agreed to jointly update the existing module on liquefaction assessment to include latest developments resulting from the Canterbury earthquakes and other major earthquakes worldwide, to accelerate the preparation of the additional modules of the Guidelines, and to use the Guidelines as a vehicle to implement many of the CERC recommendations.

This document, *Module 1*, presents an overview of the various modules that make up the *Guidelines,* see Section 6, introduces the subject of earthquake geotechnical engineering, provides context within the building regulatory framework, and provides guidance for estimating ground motion parameters for geotechnical design.

The science and practice of earthquake geotechnical engineering is far from mature and is advancing at a rapid rate. It is intended that the Guidelines will be updated periodically to incorporate new advances in the field but these updates will, naturally, lag behind the very latest advances. It is important that users of this document familiarise themselves with the latest advances and amend the recommendations herein appropriately.

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1 INTRODUCTION

New Zealand is a high earthquake hazard region and earthquake considerations are integral to the design of the built environment in New Zealand. The effects of earthquake shaking need to always be considered in geotechnical engineering practice and frequently are found to govern design.

Earthquake geotechnical engineering is a relatively young discipline of civil engineering that considers the geotechnical aspects of the wider discipline of earthquake engineering. Geotechnical conditions are critical to understanding the intensity and pattern of damaging ground shaking at a site. Ground failure from site instability, soil softening especially liquefaction, and lateral spreading are significant earthquake hazards. The design of foundations, retaining structures, roads, and buried infrastructure to resist earthquake shaking and ground failure requires special consideration.

The high seismic hazard in New Zealand and profound relevance of earthquake geotechnical engineering were demonstrated by the Canterbury Earthquake Sequence. Christchurch and Canterbury were hit hard by a series of strong earthquakes generated by previously unmapped faults located in the vicinity or within the city boundaries. In the period between 4 September 2010 and December 2011, the intense seismic activity produced the magnitude (M_W) 7.1 Darfield event, the destructive 22 February 2011 M_W 6.2 earthquake, 12 other M_W 5 to 6 earthquakes, and over one hundred M_W 4 to 5 earthquakes. The 22 February 2011 earthquake was the most devastating causing 185 fatalities, the collapse of two multi-storey buildings, and the need for nearly total rebuild of the Central Business District.

The geotechnical aspects and impacts of the earthquakes were of economic and societal significance. The Canterbury earthquakes triggered widespread liquefaction in the eastern suburbs of Christchurch, as well as rock slides, rockfalls and cliff instabilities in the Port Hills affecting tens of thousands of residential buildings, and causing extensive damage to the lifelines and infrastructure over much of the city. About half of the total economic loss could be attributed to the geotechnical impacts of the earthquake-induced liquefaction and rockslides.

1.1 Objective

While there is a substantial and rapidly growing body of published research on the subject of earthquake geotechnical engineering, most of this information is relatively dispersed in journal articles and conference proceedings making it difficult for practising engineers to keep abreast of developments and what may be considered 'state of practice'. There are few comprehensive text books or monographs on the subject with some notable exceptions. (Kramer, 1996; Towhata, 2008).

The objective of the Guidelines is to help summarise current practice in earthquake geotechnical engineering with a focus on New Zealand conditions, regulatory framework, and practice. The Guidelines are not intended to be a detailed treatise of latest research in earthquake geotechnical engineering, which continues to advance rapidly. Instead, this document is intended to provide sound guidelines to support rational design approaches for everyday situations, which are informed by latest research. Complex and unusual situations are not covered. In these cases special or site-specific studies are considered more appropriate.

The main purpose of the Guidelines is to promote consistency of approach to everyday engineering practice in New Zealand and, thus, improve geotechnical-earthquake aspects of the performance of the built environment.

These Guidelines are not a book of rules – users are assumed to be qualified, practicing geotechnical engineering professionals with sufficient experience to apply professional judgement in interpreting and applying the recommendations contained herein.

Neither are the Guidelines intended to be a primer on the subject of earthquake geotechnical engineering – readers are assumed to have a sound background in soil mechanics, geotechnical engineering, and earthquake engineering. A thorough foundation for earthquake geotechnical engineering is provided by Kramer (1996) and users of the Guidelines should be familiar with the material covered therein.

The science and practice of earthquake geotechnical engineering is advancing at a rapid rate. The users of this document should familiarise themselves with recent advances and interpret and apply the recommendations herein appropriately.

1.2 Intended audience

These Guidelines have been prepared, generally, for the use of qualified, practising geotechnical engineers with a sound background in soil mechanics, geotechnical engineering, and earthquake engineering.

Module 2: Site Investigations, is intended to be used by both qualified, practising geotechnical engineers and engineering geologists to guide planning and execution of geotechnical investigations.

Module 4: Foundations, and *Module 6: Retaining Walls*, will also be of interest to practising structural engineers although it is intended that they should work in close collaboration with geotechnical engineering professionals to develop designs for significant building foundations and retaining structures.

1.3 Professional collaboration

Geotechnical considerations are crucial to successful designs for any part of the built environment, especially in New Zealand's high earthquake hazard environment. Successful outcomes require close collaboration among the key professionals (geotechnical engineers, engineering geologists and structural engineers) to properly consider the site geology, earthquake hazards, site response, soil response, foundation behaviour, structural interactions and soil-structure system response.

A proper understanding of the site geology is essential and requires collaboration between the geotechnical engineer and engineering geologist with inputs from the structural engineer to understand the site requirements for the proposed structure and any possible site-structure interactions.

A full consideration of the site response and soil response to shaking together with a sound understanding of the structural response including soil-structure interaction is essential to make appropriate selections of suitable foundation types or ground treatments, requiring close collaboration between the geotechnical and structural engineers.

Geotechnical and structural engineers may have different performance objectives in mind, or simply do not clearly understand what each discipline contributes or is able to contribute to the design process, or what actually matters for design (Oliver et al, 2013).

Close collaboration does not mean each professional preparing a report and sending the other a copy. It means sitting down together and sharing each professional's perspective of the project and coming to a shared understanding of all of the issues and interactions required for a successful outcome. The result would ideally be a joint report outlining the expected performance of the site, ground, foundations, and structure including their critical interactions.

1.4 General assessment principles

Earthquake geotechnical engineering problems require adequate treatment in all phases of the assessment procedure, including evaluation of seismic loads, site investigations, hazard identification, site and soil characterisation, use of appropriate assessment methodology, analyses, interpretation and engineering judgement. Consideration of uncertainties is critically important throughout the assessment process. The level of detail and particular features of the assessment procedure should be balanced across all phases. They also should be appropriate for the scale of the project, the importance of the facilities planned for the site, the level of risk associated with the hazard and potential consequences of failure in terms of loss of life, economic loss, and impacts on communities.

Geotechnical professionals increasingly rely on computer software to carry out analysis and design including liquefaction assessments, slope stability assessments, foundation design, and advanced numerical modelling using finite element and finite difference methods. The benefits include increased productivity and, when used properly, useful additional insights from parametric studies and rapid prototyping.

However, users need to have a sound understanding of the analysis methods being implemented within each software package including the inherent limitations and uncertainties of each, otherwise the results may be misleading and potentially dangerous. The quality and reliability of the outputs directly depends on the quality of the inputs – mainly soil parameters that are intrinsically variable and difficult to measure. Uncertainties in both input parameters and output results should be considered by use of parametric and sensitivity studies, and by use of multiple analysis methods or models. It remains the professional responsibility of the user to interpret and validate the results based on expertise and engineering judgement.

2 SCOPE

The material in this document relates specifically to earthquake hazards and should not be assumed to have wider applicability. It is intended to provide general guidance for earthquake geotechnical engineering practice in New Zealand.

The recommendations in this document are intended to be applied to every day engineering practice by qualified and experienced geotechnical engineering professionals who are expected to also apply sound engineering judgement in adapting the recommendations to each particular situation. Complex and unusual situations are not covered. In these cases special or site-specific studies are considered more appropriate and additional guidance sought.

Other documents may provide more specific guidelines or rules for specialist structures, and these should, in general, take precedence over this document.

Examples include:

- *New Zealand Society on Large Dams – Dam Safety Guidelines*
- *NZ Transport Agency – Bridge Manual*
- *Transpower New Zealand – Transmission Structure Foundation Manual.*

Where significant discrepancies are identified among different guidelines and design manuals, it is the responsibility of the engineer to resolve such discrepancies as far as practicable.

The recommendations made in this document may seem excessive or burdensome for very small projects such as single unit dwellings. The intention is that earthquake hazards (and all geotechnical hazards) should be properly investigated and assessed at the subdivision stage of development when appropriate expenditures can be more easily justified. Simpler investigations and assessments would be then likely be adequate for individual sites. Professional judgement needs to be applied in all cases.

More specific guidance has been issued by MBIE for the repair and rebuilding of residential dwelling foundations in the Canterbury earthquake region (MBIE, 2012) and this should take precedence over these Guidelines. However, the MBIE Guidance is specifically for use within the Canterbury earthquake region only and it may not be appropriate to use it elsewhere.

3 GEOTECHNICAL CONSIDERATIONS FOR THE BUILT ENVIRONMENT

Clause B1 of the *Building Code* expands on the general purpose of the *Building Act* to ensure safety by including objectives to:

- safeguard people from injury caused by structural failure
- safeguard people from loss of amenity caused by structural behaviour
- protect other property from physical damage caused by structural failure.

Buildings, building elements and site-works are required to have a low probability of:

- rupturing, becoming unstable, losing equilibrium or collapsing during construction, alteration, and throughout their lives
- causing loss of amenity through undue deformation, vibratory response, degradation, or other physical characteristics throughout their lives, during construction, alteration, or when the building is in use.

Account is required to be taken of various physical conditions including:

- earthquake
- earth pressure
- differential movement
- time-dependent effects such as creep and shrinkage
- removal of support.

Site-work is required to be carried out so as to provide stability for construction and to avoid the likelihood of damage to other property. It must achieve this while taking account of:

- changes in ground water level
- water, weather and vegetation
- ground loss and slumping.

Geotechnical considerations are clearly an essential part of the design and construction of any building development. Failing to demonstrate compliance with the above requirements because of geotechnical deficiencies would result in failure to obtain a building consent.

Issue of a building consent would also be dependent on the land generally meeting the stability requirements of the *Resource Management Act*. Section 106 gives a consenting authority the power to refuse a subdivision consent if the land is subject to erosion, subsidence, slippage or inundation. Section 220 refers to similar criteria.

Geotechnical considerations are crucial to successful design of any part of the built environment. There is a strong need to raise awareness of the importance of the application of geotechnical skills and knowledge in every

aspect of building developments. This will involve the following:

- a review of the geological, seismological, and geotechnical context of the development site
- specific investigation and gathering of geotechnical and related data
- development of geotechnical design parameters appropriate to the building development and the site
- due account of geotechnical considerations in the design of the building development so that it meets the requirements of the building code
- due consideration of geotechnical factors, including overall land stability, prior to the issue of resource and building consents
- review of geotechnical conditions and modification of design details as necessary during construction.

While not explicitly stated, for each of these factors, due consideration of the effects of earthquakes (ground shaking, ground deformation and failure, and fault displacements) must clearly be included in every geotechnical assessment.

A more detailed overview of the New Zealand building regulatory system is given in Appendix B.

4 EARTHQUAKE GEOTECHNICAL HAZARDS

Earthquakes are sudden ruptures of the earth's crust caused by accumulating stresses (elastic strain-energy) resulting from internal processes of the planet. Ruptures propagate over approximately planar surfaces called faults releasing large amounts of strain energy. Energy radiates from the rupture as seismic waves. These waves are attenuated, refracted, and reflected as they travel through the earth, eventually reaching the surface where they cause ground shaking. Surface waves (Rayleigh and Love waves) are generated where body waves (p-waves and s-waves) interact with the earth's surface.

The principal geotechnical hazards associated with earthquakes are:

1 Fault rupture
2 Ground shaking
3 Liquefaction and lateral spreading
4 Landslides and rockfalls
5 Tsunami.

Each of these hazards is described in more detail below.

4.1 Fault rupture

For shallow earthquakes, the fault rupture may extend to the ground surface generating scarps and lateral offsets of up to several metres. The extent of surface deformation is dependent on the type of fault and the depth and nature of surface soils. These deformations may be very damaging to buried services, roads, dams and railways. Light structures may be torn apart if the surface fault rupture dissects the building footprint. For heavier, stronger structures (for example, reinforced concrete buildings of more than three storeys on thick soil deposits), the surface fault rupture may locally deviate around the building footprint because of the effect of the additional soil confining pressure and strength of the building foundation relative to the ground beneath it (Bray, 2009). Note however that such rupture deviation due to presence of strong and robust structures does not always occur, and that faults have ruptured through large dams.

Ground subsidence induced by fault or tectonic movement involving relatively large areas may occur during strong earthquakes. Subsidence is often accompanied by inundation and damage to engineering structures over extensive areas, particularly in coastal regions.

The location of known active faults in New Zealand should be obtained from the latest available geological mapping for a site. Active fault locations are also usually shown on the planning maps of Territorial Local Authorities. Many active faults are shown in the GNS active faults database (http://data.gns.cri.nz/af/). The accuracy of such maps varies and the source data (trenches, geophysics, aerial photographs, etc.) should be consulted wherever possible.

Wherever doubt exists, trenching or other means (geophysics, CPTs and boreholes) should be used to establish the location (or locations) of an active fault trace near to or on a site. It is important to recognise that there are many unknown faults in addition to the mapped faults. Such unknown (unmapped) faults are incorporated through specific considerations and assumptions in the seismic hazard analysis.

Refer to: *Planning for Development of Land on or Close to Active Faults – A guideline to assist resource management planners in New Zealand*, a report published by the Ministry for the Environment.

4.2 Ground shaking

Ground shaking is one of the principal seismic hazards that can cause extensive damage to the built environment and failure of engineering systems over large areas. Earthquake loads and their effects on structures are directly related to the intensity, frequency content, and duration of ground shaking. Similarly, the level of ground deformation, damage to earth structures and ground failures are closely related to the severity of ground shaking.

In engineering evaluations, three characteristics of ground shaking are typically considered:

- amplitude
- frequency content
- duration of significant shaking (ie time over which the ground motion has significant amplitudes)

These characteristics of the ground motion at a given site are affected by numerous complex factors such as the source-to-site distance, earthquake magnitude, effects of local soil and rock conditions, rupture directivity, topographic and basin effects, source mechanism, and propagation path of seismic waves. There are many unknowns and uncertainties associated with these factors which in turn result in significant uncertainties regarding the characteristics of the ground motion and earthquake loads. Hence, special care should be taken when evaluating the characteristics of ground shaking including due consideration of the importance of the structure and particular features of the adopted analysis procedure.

Information on estimating ground motion parameters for earthquake geotechnical engineering purposes is provided in Section 5 of this Module.

4.3 Liquefaction and lateral spreading

The term 'liquefaction' is widely used to describe ground damage caused by earthquake shaking even though a number of different phenomena may cause such damage.

Liquefaction is associated with significant loss of stiffness and strength in the liquefied soil and consequent large ground deformation as a result of the development of large excess pore water pressures within the soil. Particularly damaging for engineering structures are cyclic ground movements during the period of shaking and excessive residual deformations such as settlements of the ground and lateral spreads.

Ground surface disruption including surface cracking, dislocation, ground distortion, slumping and permanent deformations, such as large settlements and lateral spreads, are commonly observed at liquefied sites. Sand boils, including ejected water and fine particles of liquefied soils, are also typical manifestations of liquefaction at the ground surface. In cases of massive sand boils, gravel-size particles and even cobbles can be ejected on the ground surface due to seepage forces caused by high excess pore water pressures. Note that sediment (silt, sand, gravel) ejecta are clear evidence of soil liquefaction, however they do not always occur at liquefied sites.

In sloping ground and backfills behind retaining structures in waterfront areas, liquefaction often results in large permanent ground displacements in the down-slope direction or towards waterways (lateral spreads). In the case of very loose soils, liquefaction may affect the overall stability of the ground leading to catastrophic flow failures. Dams, embankments and sloping ground near riverbanks where certain shear strength is required for stability under gravity loads are particularly prone to such failures.

Clay soils may also suffer some loss of strength during shaking but are not subject to boils and other 'classic' liquefaction phenomena. However, for weak normally consolidated and lightly over-consolidated clay soils the demand may exceed the undrained shear strength during shaking leading to accumulating shear strain and damaging ground deformations. If sufficient shear strain accumulates, sensitive soils may lose significant shear strength leading to slope failures, foundation failures, and settlement of loaded areas. Ground deformations that arise from cyclic failure may range from relatively severe in natural quick clays (sensitivity greater than eight) to relatively minor in well-compacted or heavily over-consolidated clays (low sensitivity). Studies by Boulanger and Idriss (2006, 2007), and Bray and Sancio (2006) provide useful insights. The summary in Idriss and Boulanger (2008) is helpful in clarifying issues regarding soil liquefaction and cyclic softening of different soil types during strong ground shaking.

For intermediate soils, the transition from 'sand-like' to 'clay-like' behaviour depends primarily on the mineralogy of the fine-grained fraction of the soil and the role of the fines in the soil matrix. The fines content of the soil is of lesser importance than its clay mineralogy as characterised by the soil's plasticity index (PI). Engineering judgement based on good quality investigations and data interpretation should be used for classifying such soils as liquefiable or non-liquefiable. Bray and Sancio (2006), Idriss and Boulanger (2008), and other studies provide insights on the liquefaction susceptibility of fine-grained soils such as low plasticity silts and silty sands with high fines contents. If the soils are classified as 'sand-like' or liquefiable, then triggering and consequences of liquefaction should be evaluated using procedures discussed in this document and Module 3. On the other hand, if the soils are classified as 'clay-like' or non-liquefiable, then effects of cyclic softening and consequent ground deformation should be evaluated using separate procedures.

> Information on the identification, assessment and mitigation of liquefaction hazards is provided in Module 3 of the Guidelines.

4.4 Landslides and rockfalls

Landslides are a familiar geotechnical hazard in many parts of New Zealand. The rate of incidence of landslides is at its highest during or following high rainfall intensity events, but earthquakes also trigger many landslides, including very large, dangerous rock slides. Ground accelerations caused by earthquake shaking can significantly reduce the stability of inclined masses of soil and rock. Even though the acceleration pulses may be of short duration, they may be sufficient to trigger rockfalls or initiate an incipient failure, especially where the soil or rock is susceptible to strain softening or brittle failure.

Earthquake-induced landslides usually affect large areas in the source zone, or even greater areas beyond the immediate source zone in the case of large magnitude earthquakes. As demonstrated in the Canterbury earthquakes, rockfalls, slope instabilities, and associated hazards are very difficult to deal with, and are particularly challenging in an urban setting. This is because they involve large volumes of marginally stable fractured rocks that are difficult to approach, stabilise and mitigate in a cost-effective manner.

Geotechnical evaluation of seismic stability of slopes and rockfalls typically involves assessment of stability under earthquake loading (triggering issues), permanent displacements of slides and rockfalls (run-out distance), and engineering mitigation measures.

> Information on the assessment and mitigation of slope instability and rockfalls may be provided in a future Module of the Guidelines.

4.5 Tsunami

Tsunami has not been recognised as a principal geotechnical hazard. However, in the 2011 Great East Japan (Tohoku) Earthquake, a tsunami triggered a large number of geotechnical failures of sea walls, breakwaters, river dikes and buildings causing tremendous physical damage and loss of life. In this context, due consideration of potential tsunami hazard must clearly be included in the geotechnical evaluation of structures that are exposed to tsunami hazard.

> NZGS has no present plans to include assessment or mitigation of tsunami hazard within the Guidelines.

5 ESTIMATING GROUND MOTION PARAMETERS

Earthquakes occur on faults with a recurrence interval that depends on the rate of strain-energy accumulation. Intervals vary from hundreds to tens of thousands of years. There is much uncertainty over the variability of the strain rate over time, the recurrence interval, the time since the last rupture, the activity of a fault, and the location of active faults.

Due to the uncertainty in predicting earthquake events, a statistical approach is usually adopted to assess the seismic hazard at any location. The level of hazard varies significantly across New Zealand with very high levels near to the Australia/Pacific plate boundary where high rates of tectonic displacement occur. The seismic hazard generally decreases with distance from this zone.

For engineering evaluation of liquefaction phenomena and other problems in earthquake geotechnical engineering, the amplitude (commonly represented by the largest value of acceleration recorded during the earthquake, ie the peak horizontal ground acceleration, a_{max}) and the duration of ground shaking (related to earthquake magnitude, M_W) are the key input parameters to most common design procedures, with no direct consideration of the frequency (represented by the response spectrum).

As incoming seismic waves travel from relatively stiff bedrock into much softer soils at a site, they slow down and the amplitude of shaking increases. Certain frequencies may be amplified depending on the stiffness, thickness, density and geometry of the soil deposit at the site and the amplitude of shaking. For very strong shaking there may be attenuation of a_{max} and increased displacement amplitude caused by yielding of weak soils and filtering of certain frequencies because of the non-linear, strain-dependent stiffness and damping of soil.

Fault rupture in large earthquakes may involve surfaces of many kilometres in extent. Rupture typically initiates at a point and then propagates along the fault surface at a velocity similar to that of seismic wave propagation. When rupture propagates toward a site, the energy released by the fault rupture can build-up and produce intense ground motions with distinctive velocity pulses.

These forward-directivity near-fault motions have relatively short durations, but high intensity. Backward-directivity motions are less intense but longer in duration.

The ground shaking hazard at a site depends on the following parameters:

- amplitude, frequency content and duration of shaking at bedrock beneath the site
- thickness and properties of soil strata beneath the site and overlying the bedrock, as well as bedrock properties themselves
- proximity of the site to active faults (including near-fault effects)
- three-dimensional relief both of the surface contours and sub-strata.

The ground motion parameters at a site for problems in earthquake geotechnical engineering including liquefaction hazard assessment may be evaluated using one of the following methods:

1 *Method 1: Risk based method using the earthquake hazard presented in the NZTA Bridge Manual [2014]*

2 *Method 2: Site-specific probabilistic seismic hazard analysis*

3 *Method 3: Site-specific response analysis*.

Method 1 is appropriate for routine engineering design projects. Methods 2 and 3 are preferred for more significant projects, more complex sites, or other cases where advanced analysis can be justified.

5.1 **METHOD 1:** Risk-based method using earthquake hazard estimates presented in the NZTA Bridge Manual

The NZTA Bridge Manual (2014) presents unweighted seismic hazard factors (peak ground acceleration coefficients) and corresponding (effective) earthquake magnitudes to be used in liquefaction triggering analyses and assessment of the stability and displacements of slopes and earth retaining structures. These factors were derived from results of a probabilistic seismic hazard model developed by the Institute of Geological and Nuclear Sciences (Stirling et. al., 2000, 2002). The hazard model was substantially updated in 2010 (Stirling et al, 2011), but at the time of publication of these guidelines the results from the update study have not been incorporated widely into national standards (including the NZTA Bridge Manual).

The use of seismic hazard factors (Z factors) presented in NZS 1170.5:2004 are no longer recommended because they were derived using a magnitude weighting process that is incompatible with the latest liquefaction triggering analyses (eg Boulanger & Idriss, 2014) and with other geotechnical design issues including site stability analysis, landslide and rockfall analysis, and retaining wall design.

For Class D sites in the Canterbury Earthquake Region (defined as the jurisdictions of the Christchurch City Council, the Selwyn District Council, and the Waimakariri District Council) values of a_{max} and magnitude to be used for liquefaction triggering analyses have been prescribed by the Ministry of Business, Innovation, and Employment (MBIE) based on studies taking into account the short and medium term increase in seismic hazard for the Canterbury Region due to the elevated seismicity caused by the Canterbury Earthquake Sequence.

For all locations ***excluding*** the Canterbury Earthquake Region the following procedure from NZTA (2014) is recommended:

Peak horizontal ground acceleration (a_{max}) may be calculated as:

$$a_{max} = C_{0,1000} \frac{R}{1.3} f g$$

in which:

$C_{0,1000}$ = Unweighted peak ground acceleration coefficient corresponding to a 1000 year return period from Figure A.1 (see Appendix A) for Class A, B, (rock) or C (shallow soil) sites or from Figure A.2 for Class D or E (soft, deep soil) sites.

R = return period factor and is given by NZS 1170.5:2004 Table 3.5

g = acceleration from gravity

f = site response factor:

Class A, B	Rock sites	$f = 1.0$
Class C	Shallow soil	$f = 1.33$
Class D, E	Soft, deep soil	$f = 1.0$

The earthquake effective magnitude is given in Figures A.3 to A.7 and depends on the particular earthquake return period being considered.

Guidance on selection of appropriate return periods for a particular facility is given in NZS 1170.0 Table 3.3. Typically, for buildings of normal use (Importance Level 2) earthquake motions with a return period of 500 years (R = 1) are used for the ultimate limit state (ULS) and 25 years (R = 0.25) are used for the serviceability limit state (SLS). Note that NZTA values for the effective magnitude are not available for a 25 year return period. Instead the values for the 50 year return period are suggested for SLS analysis. The use of the slightly longer return period values in most circumstances would not be expected to have a significant impact on the results of analyses.

Descriptions of the different site soil classes are given in NZS 1170.5:2004 clauses 3.1.3.2 to 3.1.3.6 and in Table 3.2. Selection of the appropriate site soil class should be based on knowledge of the site soil profile to bedrock. Larkin & Van Houtte (2014) provides further guidance.

For locations within the Canterbury Earthquake Region the following procedure is ***required*** for the purpose of assessing liquefaction hazard:

Canterbury Earthquake Region

The following recommended values of a_{max} and effective earthquake magnitude, M_W for Class D sites (deep and/or soft soil sites) within the Canterbury earthquake region for liquefaction-triggering analysis only are given below. The annual probability of exceedance is considered to be the average over the next 50 years, considered appropriate for Importance Level 2 buildings.

SLS $a_{max} = 0.13$ g, $M_W = 7.5$

and $a_{max} = 0.19$ g, $M_W = 6$

ULS $a_{max} = 0.35$ g, $M_W = 7.5$

For the SLS, both combinations of a_{max} and M_W must be analysed and the highest calculated total volumetric strain resulting from liquefaction under either scenario adopted. The worst case scenario should be considered.

For Class D sites outside of Christchurch City and still within the Canterbury Earthquake Region, especially sites closer to the Southern Alps and foothills, it is recommended that design a_{max} values be taken as the greater of these values and those from the NZTA Bridge Manual.

These values of a_{max} have been classified as interim guidance by MBIE. The Ministry has advised that further, more comprehensive guidance may be given as a result of on-going model refinement. Reference should be made to the MBIE website for the latest updates.

Note: The ground motion parameters (PGA and M_W) define the earthquake loading required in liquefaction assessment and earthquake geotechnical engineering evaluations. The Canterbury earthquakes have led to further scrutiny of New Zealand seismic hazard characterization, and several issues with the seismic hazard presented in NZS 1170.5 and NZTA Bridge Manual have been identified. These include:

1. compatibility issues between the magnitude weighting factors embedded in the hazard evaluation and the magnitude scaling factors in the liquefaction evaluation procedures adopted in this guideline series
2. the use of an 'effective earthquake magnitude', and
3. the need for updates in the seismic hazard model.

Considerations of elevated seismicity due to the Canterbury earthquake sequence and the consequent MBIE interim guidance for the Canterbury Earthquake Region also adds to the complexity of the hazard interpretation. Work is in progress to address these issues and provide improved procedures. Meanwhile, the recommended use of NZTA Bridge Manual ground motion parameters when using Method 1 is a step forward from the NZS1170.5 approach and will provide greater consistency for routine engineering projects in the interim. Reference should be made to the MBIE and NZGS websites for the latest updates.

5.2 **Method 2:** Site-specific probabilistic seismic hazard analysis

Method 2 is preferred to Method 1 for important structures. Method 2 allows site specific peak ground accelerations and/or spectra to be developed for the location of interest and for the site subsoil class, rather than scaling these from the hazard factor. It also allows for updating of the seismic hazard study on which the NZTA Bridge Manual [2014] was based.

The justification for performing a Method 2 analysis is based on the reasoning that:

1. site-specific analysis will provide more accurate modelling of the earthquake loading, site effects, and seismic response
2. de-aggregation of the site specific seismic hazard will provide essential input for scenario earthquake analyses, and also SLS and ULS performance evaluations; and
3. site-specific analyses could incorporate new information and updated modelling of the hazard using most recent studies and data.

Where a site specific seismic hazard analysis has been carried out, multiple scenarios using different combinations of a_{max} and effective M_W should be made available for liquefaction triggering assessments.

Comment: *The effect of earthquake magnitude in assessing the risk of liquefaction triggering has received increased significance in the latest update of the simplified procedure [eg Boulanger and Idriss, 2014]. Earthquakes of higher magnitude may trigger liquefaction at significantly lower values of a_{max} than lower magnitude events, and hence, the highest value of a_{max} estimated for the site and corresponding effective M_W may not represent the critical case.*

Method 2 site-specific probabilistic seismic hazard assessments should only be carried out by an experienced specialist.

5.3 Method 3: Site-response analysis

Method 3 involves evaluation of site-specific scale (amplification) factors through detailed site-response analyses and hence potentially provides more realistic values for site effects than Methods 1 or 2, which both use generic site-response factors according to the site subsoil class. Method 3 is appropriate for more significant projects, more complex sites, or other cases where more analysis can be justified.

Method 3 entails specific modelling of the soil profile of the site requiring more geotechnical information than Methods 1 or 2 including small-strain soil stiffness (eg from shear wave velocity, V_S, profiles) and non-linear soil stress-strain characteristics for each of the modelled soil units.

Site-specific analysis can be carried out to varying levels of complexity:

- **1–D analysis:** Various software programs are available to perform this analysis but require good judgement and a good knowledge of the soil properties and profile to bedrock for the result to be meaningful. Non-linear soil response may be modelled either through an equivalent-linear analysis or a fully non-linear analysis. When using non-linear analysis, particular care should be taken that the adopted stress-strain model accurately represents the stress-strain curve of the soil across the entire range of relevant strains including stiffness, damping and strength of the soil (ie the shear stress at failure or large strains should correspond to the dynamic shear strength of the soil). Note that some widely available non-linear models have been calibrated at small to moderate strains only, and they generally provide poor representation of soil stress-strain behaviour at strains greater than 0.5 percent or 1.0 percent. The report by Stewart et. al. (2008) provides some guidance for the application of non-linear ground response analysis procedures.
- **2–D and 3–D analyses:** Useful for sites with significant geometry effects where focussing of incoming seismic waves or superposition effects (such as at the edge of a basin or topographic features, for example Kobe 1995, Christchurch 2010 to 2011 earthquakes) may occur. The direction of incoming seismic waves may significantly affect the result and care in performing these analyses is required. These are highly specialised analyses for which no generally accepted guidance is available. Such analyses require expertise specific to this problem, and could be justified for projects of special significance or for regional micro-zoning studies.

Method 3 (site-response analysis) should only be carried out by experienced specialists.

Analyses should carefully address uncertainty in critical soil parameters by including sensitivity studies across a wide range of possible parameter values.

In the above site-specific analyses, effective stress analysis is encouraged to be used in cases where effects of excess pore pressures are significant and where such analysis can be justified.

6 GUIDELINE MODULES

This section gives a brief description of the objective and contents of each of the individual modules. Each module is being prepared by a separate working group and each is at a different state of completion.

Refer to either the New Zealand Geotechnical Society's website www.nzgs.org/publications/guidelines.htm or to MBIE's website www.building.govt.nz for the latest edition and current status of each module.

6.1 MODULE 1: Overview of the guidelines

Module 1 provides an introduction to the Guidelines and the subject of earthquake geotechnical engineering. The objective for the Guidelines is discussed together with the intended audience. The scope of the Guidelines as a whole is described together with their status within the context of the New Zealand regulatory framework. Procedures for estimating ground motion parameters for use with problems in earthquake geotechnical engineering including liquefaction hazard assessment are provided.

6.2 MODULE 2: Geotechnical investigation for earthquake engineering

Sites to be developed as part of the built environment must be thoroughly investigated to allow identification and assessment of all geotechnical hazards, including liquefaction related hazards. Identification of liquefaction hazard at a site firstly requires a thorough investigation and sound understanding of the site geology, recent depositional history and geomorphology. The level of investigation should be appropriate to the geomorphology of the site, the scale of the proposed development, the importance of the facilities planned for the site, and the level of risk to people and other property arising from structural failure and loss of amenity.

Module 2 explains the importance of developing a geotechnical model for a site and describes the key issues to be considered. Guidance is given on planning of geotechnical site investigations. The various techniques available for sub-surface exploration are described in detail and the advantages and disadvantages of each discussed.

Guidance is provided on the preparation of geotechnical reports including appropriate matters to consider in the geotechnical factual report, geotechnical interpretive report, geotechnical design report, and geotechnical construction observation report.

Appropriate densities for site coverage of sub-surface exploration and sampling is discussed and recommendations made. The appropriate depth for sub-surface exploration is also discussed.

Some common problems encountered with site investigation works are discussed.

6.3 MODULE 3: Identification, assessment, and mitigation of liquefaction hazards

This module introduces the subject of soil liquefaction and describes the various liquefaction phenomena, including lateral spreading. Guidance is given on identification of liquefaction hazards, including a strategy for appropriate investigations, soil compositional criteria, and geological criteria. Different methodologies for assessing the risk of liquefaction triggering are discussed and recommendations made. Detailed guidance is given on the use of the 'simplified procedure' for assessing risk of liquefaction triggering considered appropriate for everyday engineering situations, together with an explanation of the limitations of this procedure.

Sources of liquefaction induced ground deformation are described and available procedures for assessing ground deformation are outlined. The residual strength of liquefied soils is discussed together with the effects of liquefaction on structures. An overview of ways and means to mitigate the effects of liquefaction and lateral spreading is provided. Numerous references are provided.

A discussion on clay soils and volcanic soils is included.

6.4 MODULE 4: Earthquake resistant foundation design

Module 4 discusses foundation performance requirements during earthquakes within the context of the New Zealand Building Code requirements. The different types of foundations in common use are described together with a strategy for selecting the most suitable type based on necessary site requirements for each. The particular issues affecting the performance of shallow foundations during earthquakes are explained and guidance on suitable design procedures given. The specific issues affecting the earthquake performance of the various types of deep foundations are discussed together with the advantages and disadvantages of each type. Guidance on analysis and design requirements for deep foundations with earthquake loading is given.

6.5 MODULE 5: Ground improvement

Module 5 considers the use of ground improvement techniques to mitigate the effects of liquefaction, cyclic softening, and lateral spreading at a site, including the effects of partial loss of soil strength through increase in pore water pressure during earthquake shaking. Guidance is provided on assessing both the need for ground improvement and the extent of improvement required to achieve satisfactory performance.

The various mechanisms for ground improvement are explained, including densification, reinforcement, drainage, chemical modification, solidification, replacement, and lowering of water table. The main techniques for ground improvement are described and discussed in some detail, including dynamic compaction, deep vibratory compaction, stone columns, reinforcement piles, lattice structures, vertical drains, and permanent dewatering.

A matrix summarising the advantages and disadvantages of each technique is presented to provide guidance in selecting the most appropriate method. The reliability and resilience of each technique is discussed and relative cost information presented.

Guidelines for designing ground improvement schemes are presented for the different techniques, together with a discussion of construction and verification considerations.

Several case studies of ground improvement projects both within New Zealand and overseas are presented together with information about actual earthquake performance.

6.6 **MODULE 5A:** Specification of ground improvement for residential properties in the Canterbury region

Module 5a provides guidance on what should be included in a technical specification when designing and constructing ground improvement for liquefaction mitigation purposes. Four ground improvement techniques are covered: Densified crust, stabilised crust, stone columns, and driven timber piles.

The guidance is intended to be limited in use to small scale ground improvement works as typically required for single residential sites (eg 500m^2 plan area). A preliminary and general specification is included together with specifications for testing, general earthworks, and technical specifications for the four ground improvement techniques. Guidance is given on how to incorporate site specific technical specifications into a construction contract for the works.

The technical specifications are based on a substantial science and research programme to test residential scale ground improvement options and to identity affordable and practical ground improvement solutions to mitigate the effects of liquefaction for residential properties by the Earthquake Commission, the US National Science Foundation, and MBIE.

The guideline was written originally for immediate use with the Canterbury earthquake recovery but is also considered generally useful for other areas within New Zealand prone to soil liquefaction.

The document does not replace the need for site specific geotechnical investigations or for the design input from a suitably experienced geotechnical engineer.

6.7 **MODULE 6:** Retaining walls

Module 6 will consider earthquake considerations for design of retaining walls.

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APPENDIX A. **UNWEIGHTED PEAK GROUND ACCELERATIONS AND EFFECTIVE EARTHQUAKE MAGNITUDES**

(from NZTA Bridge Manual, 3rd Edition, 2014)

Figure A.1: Unweighted peak ground acceleration coefficients, $C_{0,1000}$ corresponding to a 1000 year return period at a subsoil Class A or B rock site or Class C shallow soil site

Note. For Class *C* sites a scale factor of *f*=1.33 needs to be applied to the a_{max} coefficients derived from this figure.

Figure A.2: Unweighted peak ground acceleration coefficients, $C_{0,1000}$ corresponding to a 1000 year return period at a subsoil Class D or E deep or soft soil site

Figure A.3: Effective magnitudes for use with unweighted peak ground accelerations (2500 year return period)

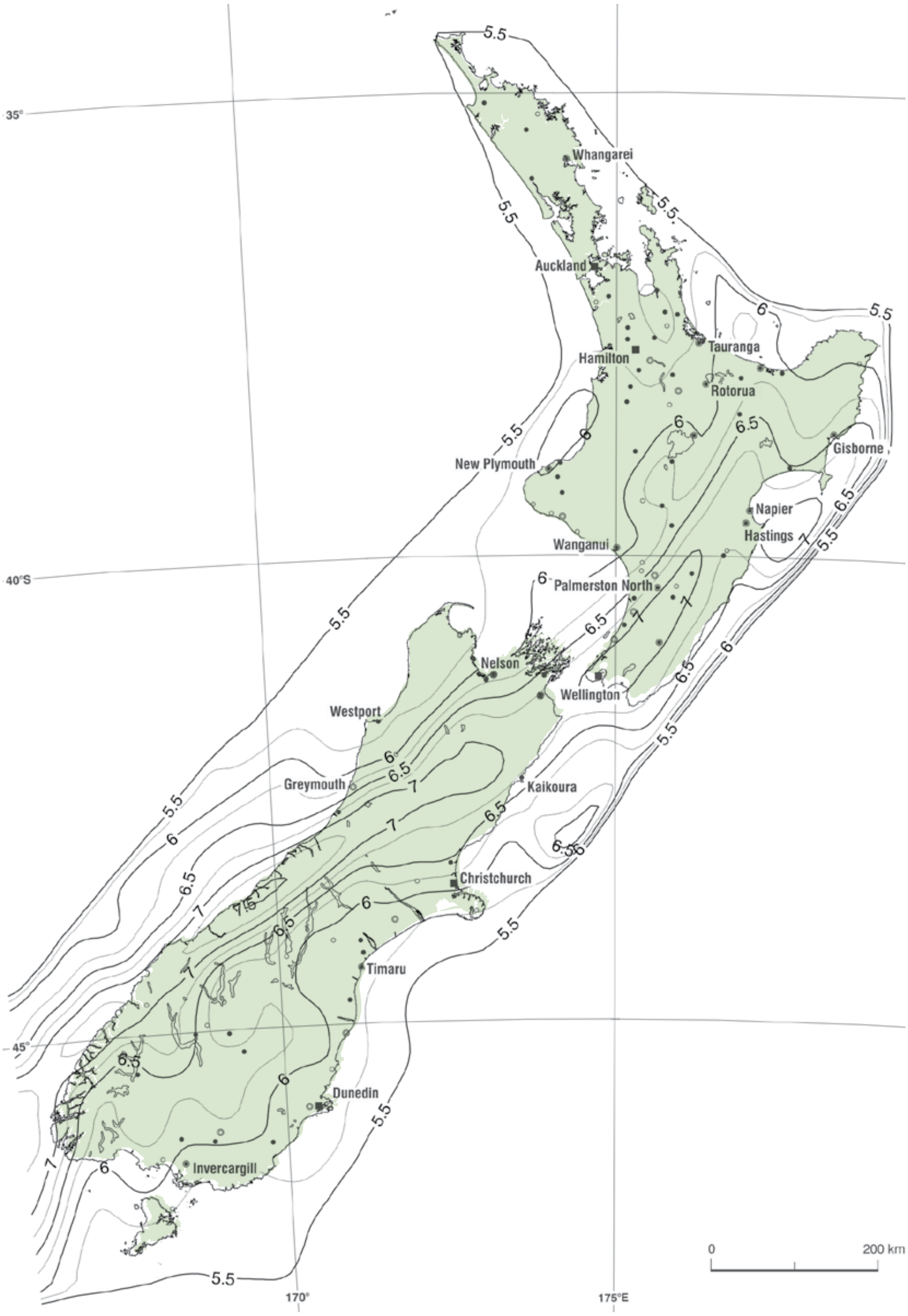


Figure A.4: Effective magnitudes for use with unweighted peak ground accelerations (1000 year return period)

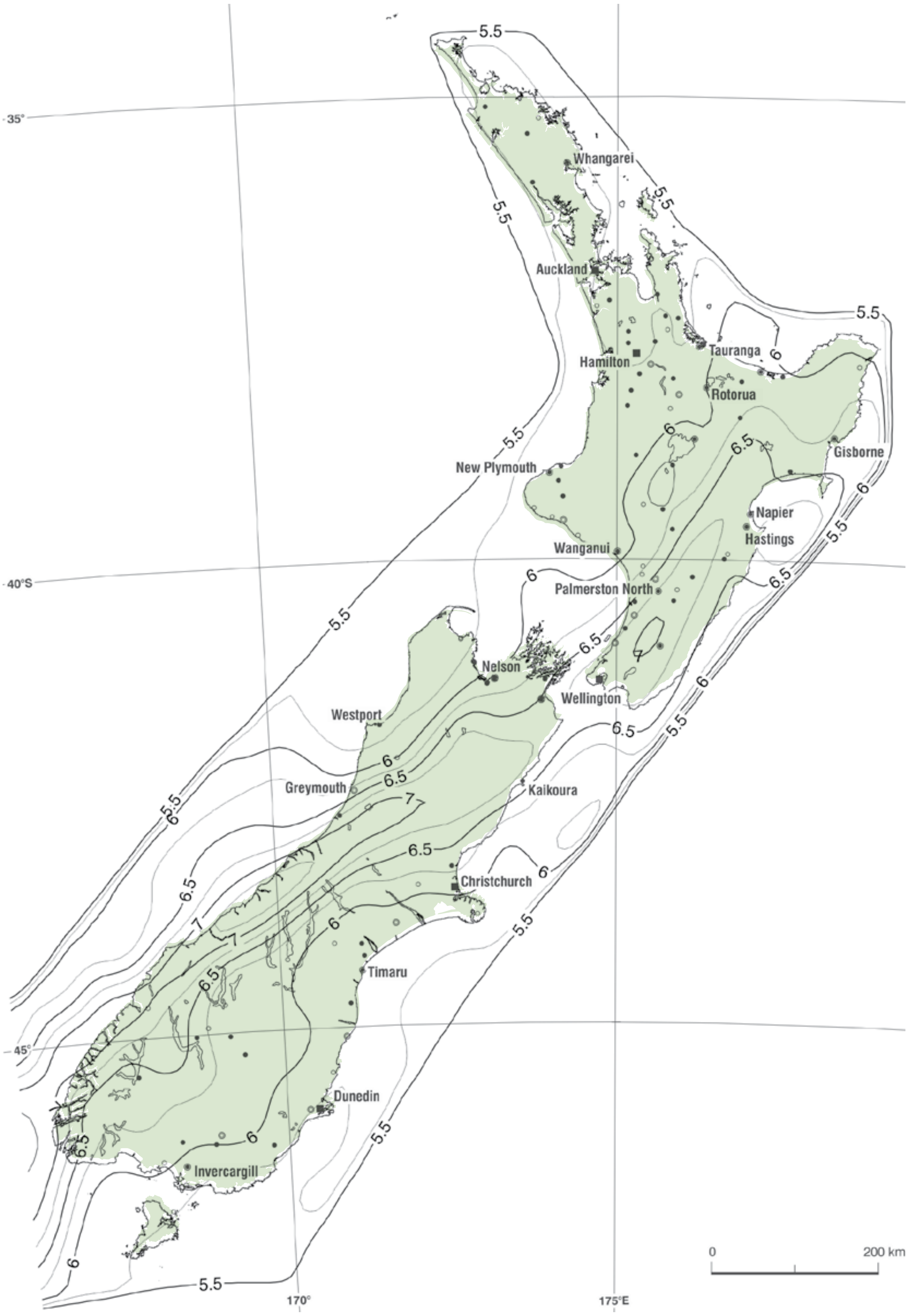


Figure A.5: Effective magnitudes for use with unweighted peak ground accelerations (500 year return period)

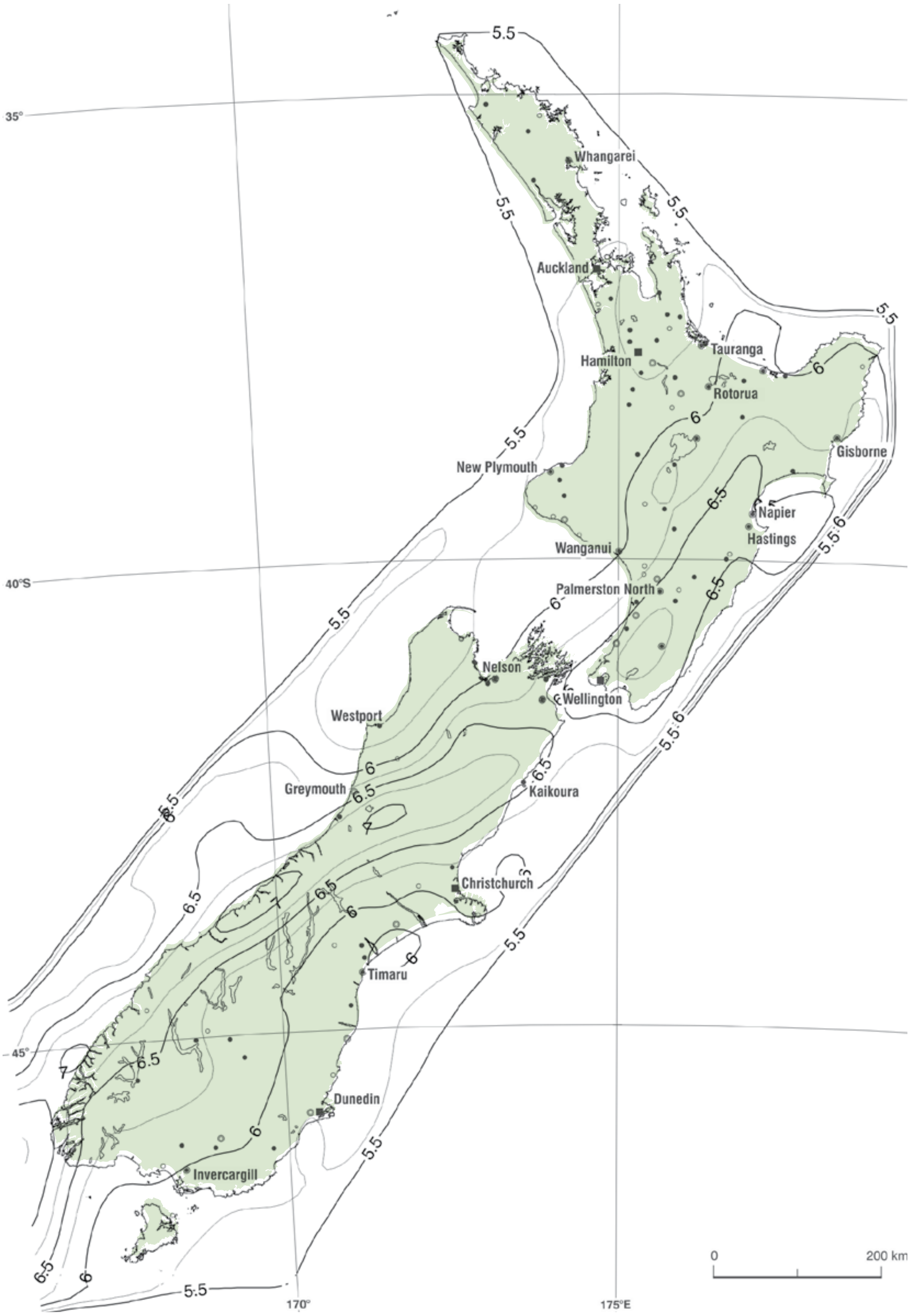


Figure A.6: Effective magnitudes for use with unweighted peak ground accelerations (100 year return period)

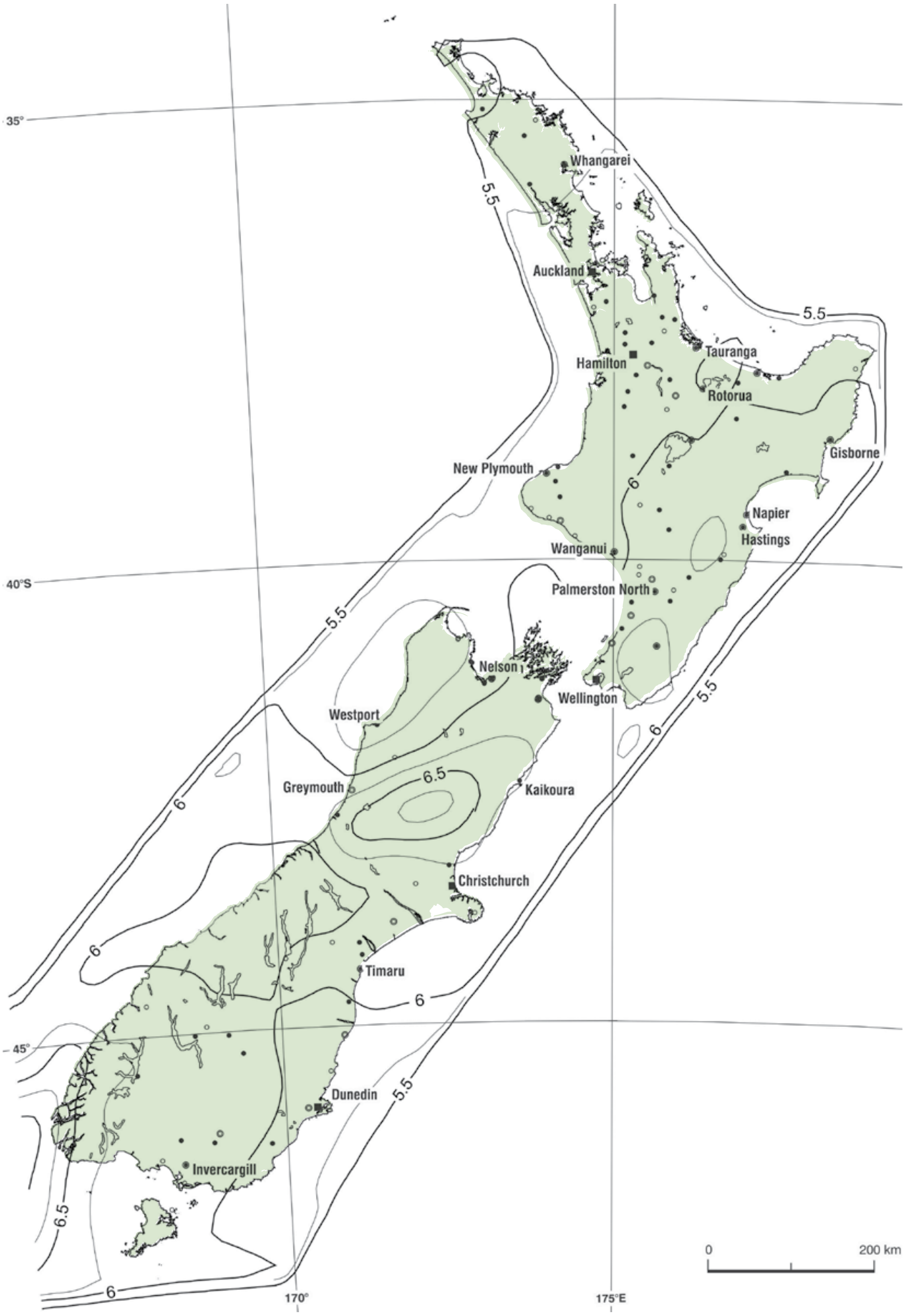
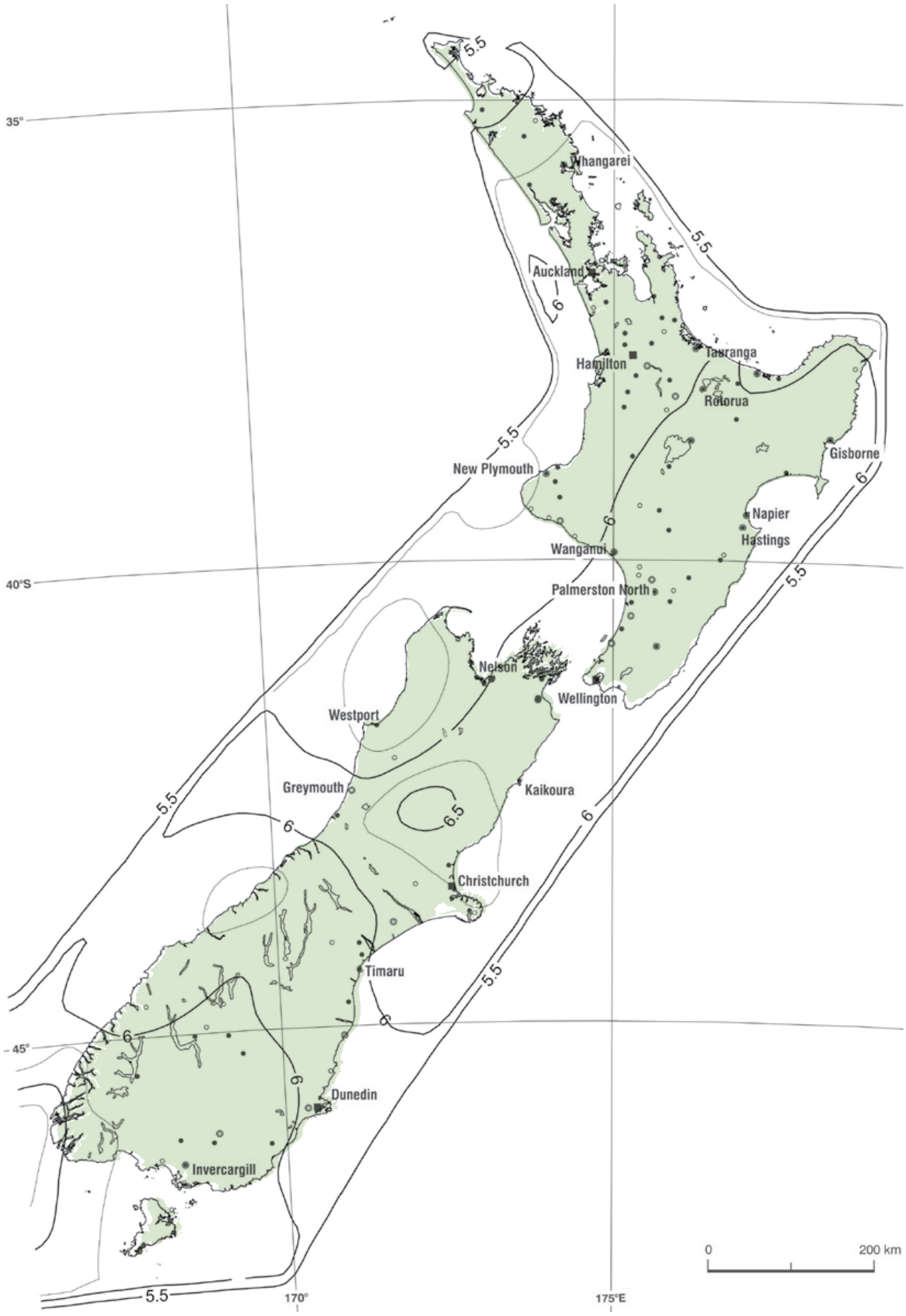


Figure A.7: Effective magnitudes for use with unweighted peak ground accelerations (50 year return period)



APPENDIX B. **NEW ZEALAND BUILDING REGULATORY SYSTEM**

B.1 Overview of the Regulatory System

The regulation and performance of buildings in New Zealand sits under the following three-part framework.

1 The Building Act (2004), which is the legislation that contains the provisions for regulating building work. It sets out the legal requirements for ensuring all new building designs, repairs, alterations, demolition and removal will comply with the supporting Building Regulations and the New Zealand Building Code.

2 The various building regulations, in particular the Building Regulations (1992) which in its Schedule 1 contains the New Zealand Building Code. The Building Code establishes a performance-based system in that it sets performance standards that all new building work must meet, covering aspects such as stability, durability, protection from fire, access, moisture, safety of users, services and facilities, and energy efficiency.

3 Verification Methods and Acceptable Solutions, which are provided for all Building Code Clauses. These provide one way (but not the only way) of complying with the Building Code. The performance-based Building Code system allows Alternative Solutions provided the design can be shown to meet the performance criteria of the Building Code, to the satisfaction of the Building Consent Authority.

B.1.1 Building Act

The Building Act principles include:

1 All Building Work needs to comply with the Building Code, whether or not a Building Consent is required (s 17)

2 Buildings need to be durable (s 4 (c)).

3 The whole-of-life costs of a building (including maintenance) need to be considered (s 4(e))

4 The importance of standards of building design and construction in achieving compliance with the Building Code (s 4(f))

5 Other property needs to be protected from physical damage resulting from the construction, use and demolition of a building (s 4(j))

6 Owners, designers, builders and building consent authorities each need to be accountable for their role in obtaining consents and approvals, ensuring plans and specifications for building work will meet the Building Code (s 4(q))

7 The Building Consent Authority must have ‘reasonable grounds’ to grant a building consent (s 49)

8 Buildings with specified intended lives (s 113)

B.1.2 Building Code

The New Zealand Building Code sets out the performance criteria to be met for all new building work. The Building Code does not prescribe how work should be done but states how completed building work and its parts must perform. The Building Code covers aspects such as stability, protection from fire, access, moisture, safety of users, services and facilities, and energy efficiency.

Buildings need to comply with all clauses of the Building Code – however Clause B1 (structure) of the Building Code is often the primary driver of the geotechnical and structural design aspect of a building. Amongst other things, B1 states that ‘buildings, building elements and sitework shall have a low probability of rupturing, becoming unstable, losing equilibrium or collapsing during construction or alteration and throughout their lives’. They should also have ‘a low probability of causing loss of amenity. . .’

The following table summarises the normal interpretation of B1:

Table B.1: Building Code Performance Requirements of Clause B1 (Structure)

CLAUSE B1 REFERENCE	PERFORMANCE CRITERIA	
	SERVICEABILITY / AMENITY	STABILITY
B1.3.1 – low probability of instability. Relates to ULS events	NA	Gross deformation of foundations that could lead to collapse to be avoided eg bearing failure, sliding.
B1.3.2 – low probability of loss of amenity. Relates to SLS events	Avoid undue deformation of foundations and structure. Building must be readily usable after the event.	NA
B1.3.3 – lists physical conditions likely to affect building stability	NA	Includes earthquake, differential movement and adverse effects on buildings such as temporary loss of geotechnical bearing capacity due to liquefaction

Of the two sets of loading criteria (ie SLS and ULS) meeting the serviceability requirements of Clause B1 on liquefiable soils can prove the more challenging. The deformation performance and its prediction are subjective issues lacking the ability to precisely calculate the effects, particularly when an SLS event could trigger liquefaction of the soils below the foundation that may or may not lead to building deformation. Secondly it is easier to calculate that a building is unlikely to collapse with modest foundation deformation.

A critical feature in meeting serviceability requirements is to demonstrate that the intended use of the building will be maintained or can be restored within a short time at reasonable cost. For instance a factory floor that has minor cracking from the effects of liquefaction in an SLS earthquake event, but the building is otherwise safe and functional could be deemed to meet the serviceability standard. However a four storey building that rotates on its foundations just sufficient to render the internal lifts inoperable will likely require closure of the upper two floors until repairs can be effected, which may take months to achieve. This latter situation could be deemed to not meet the Code for Serviceability as the upper stories have lost a key means of access that will take a long time and significant expense to reinstate.

The Building Act provides a number of pathways that designers may follow to achieve compliance with the Building Code.

1 Acceptable Solutions provide a prescriptive means of meeting the Building Code. If followed by the designer, the designer must be granted a building consent as they are deemed to comply with the Building Code. This is the simplest path.

2 Verification Methods provide a prescriptive design method, which if followed by the designer will produce a design that is also deemed to comply with the Building Code. This path does require more scrutiny than designs that follow an Acceptable Solution to check that correct assumptions and within the verification method are used and that any calculations used in the design have been done correctly.

3 Alternative Solutions whereby designers demonstrate to the satisfaction of the building consent authority (BCA) that a design solution, not covered directly with an Acceptable Solution or Verification Method, does achieve the performance requirements of the Building Code. Demonstration may include fundamental engineering design and expert review, history of use, or testing of the design or product. If it can be demonstrated to the BCA that the performance criteria are achieved, the BCA must also grant a building consent.

Section 49 of the Building Act emphasises that before a building consent can be issued the application must provide the assessing officer with confidence (on 'reasonable grounds') that, if built as specified, the building is likely to comply with the Building Code. 'Reasonable grounds' is not defined in the Act but it is usually accepted by BCAs as meaning less than a full technical review of the application. But sufficient documentation must be provided in the consent application as to create a reasonably held expectation by the BCA assessing officer that the Building Code requirements will be met. The onus is on the applicant to ensure an adequate level of work has been done to attain the reasonable grounds benchmark.

B.2 The Status and Relevance of the MBIE Guidelines for Residential Houses in Canterbury

Following the initial earthquake of the Canterbury Earthquake Sequence in 2010-11, the former Department of Building and Housing (DBH), now the Ministry of Building Innovation and Employment (MBIE) recognised that the existing design standards and Building Code did not provide adequate guidance on how to comply with the Building Code when reinstating houses damaged by the effects of liquefaction. Consequently a guideline with regular revisions was developed, setting out how to assess the degree of future liquefaction and providing suggested foundation options that would suit particular liquefaction conditions.

Development of the MBIE Guidance for house foundation replacement in Canterbury, under s.175 of the Building Act 2004, explicitly recognised that the existing Acceptable Solutions and Verification Methods did not cover foundations on liquefiable soils. Therefore many of the foundation solutions provided in the MBIE Guidance, have been developed by MBIE as Alternative Solutions (Section 8.2.1 of the MBIE Guidance 2012).

The MBIE Guidance was developed for specific application to residential properties in the Canterbury area and was not intended to be used in other parts of New Zealand. Therefore, while the guidance will serve as a useful reference for site investigation elsewhere in New Zealand, practitioners, owners and consenting authorities need to be aware of the possible limitations particularly if commercial projects are being considered or where the geological and/or seismic settings are substantially different.

NOTES