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Evolution of earthquake geotechnical engineering practice in New Zealand – the past, present and future

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ABSTRACT

Earthquake geotechnical engineering practice in New Zealand has been evolving over the past 40 years. The paper traces the evolution of design practice in the earthquake geotechnical engineering area during the past 40 years, with the research in the 1980s, the impetus provided by lifelines studies during the 1990s, development of the Bridge Manual in the 2000s and after the Canterbury earthquakes in the 2010s, in particular based on the author's experience over the past 32 years. The 2010-2011 Canterbury earthquakes provided significant impetus to the research and practice.

The Canterbury earthquakes accelerated the adoption of earthquake engineering in geotechnical practice, helped by heightened awareness of geotechnical issues such as liquefaction, increased research at the universities, and the development of industry guidance. Measures such as better definition of good ground and research into foundations in liquefiable ground helped embed the improved practice. The construction industry has also evolved significantly with contractors developing their capability for example in ground improvement, which has helped the adoption of these techniques in practice.

The paper also looks to the future, with a need to embed resilience and sustainability in our design thinking, and actively take into consideration uncertainties in hazard estimation.

1 INTRODUCTION

Geotechnical earthquake engineering has evolved in New Zealand, particularly over the past 40 years, with impetus from a variety of local and global developments. Early evolution closely followed the development of earthquake engineering for buildings, and over the past 30 years geotechnical earthquake engineering has developed on its own and in conjunction with the earthquake engineering of infrastructure.

The Canterbury earthquakes of 2010-2011 and the Kaikoura earthquake of 2016 have provided the latest impetus to the evolution. The purpose of this paper is to look at the fundamental developments over the past, how the Canterbury and Kaikoura earthquakes have given impetus, and look at what challenges require focus for the future.

2 HISTORICAL EVOLUTION 1931 TO 1990

Globally earthquake engineering had evolved as engineers learnt from the consequences and observations following past earthquakes. In New Zealand, the M7.8 Napier earthquake which devastated the city of Napier, see Figure 1, led to focus on the design for earthquakes. Early focus of earthquake engineering was on buildings and life safety, as there were many fatalities in earthquakes. This has meant that a lot of our standards and codes have a focus on life safety. This led to the gradual development of codes of practice and standards for the earthquake design of buildings.

Figure 1: Painting of the devastation caused by the 1931 Napier earthquake, New Zealand

Even though, the Napier earthquake caused geotechnical failures, such as landslides, liquefaction and lateral spreading, see Figure 2, which we can recognise today, these were not well understood or catered for in design for a long time. Even though the photographs show the impact the earthquakes on infrastructure facilities such as the port, roads, railway and fuel transportation, the focus was largely on buildings because of the loss of life due to the collapse or damage of buildings. This also led to a primary focus on life safety to avoid the loss life, in the building codes and standards that evolved.

The development of building codes following the Napier earthquake has been documented by Megget (2006). There is little reference to geotechnical design issues in the early codes.

Development of earthquake design standards and design practice in countries such as New Zealand, has meant that the collapse of buildings and associated loss of life in earthquakes has been limited, although not completely avoided as two buildings did collapse leading to significant loss of life in the 2011 Christchurch earthquake. Confidence in the ability to avoid collapse of buildings among earthquake engineers has led to increasing attention on the performance of our built environment in earthquakes and their ability to continue to function for the benefit of society.

Figure 2: Geotechnical failures in the 1931 Napier earthquake L: landslide, R: Liquefaction lateral spread

Figure 3: Damage to infrastructure from geotechnical failures in the 1931 Napier earthquake

The large programme of infrastructure development in the 1960s to 1980s led to the question of how to design these for earthquakes and led to research into earth pressures and the effect of earthquakes on earth retaining structures, such as retaining walls (Nageh, 1982, Fairless, 1984, Bracegirdle, 1987, Wood, 1985). Fairless (1984) also carried out a valuable research into the incidence of liquefaction in New Zealand, following on from global developments such as the work by Seed and Idriss (1982) on liquefaction. Berrill (x) also identified in further detail the effects of liquefaction from past earthquakes in Christchurch.

An examination of 1980s geotechnical reports prepared for buildings damaged in the Canterbury earthquakes indicated that there was little attention given to liquefaction or the risk to high rise buildings in Christchurch.

3 EVOLUTION IN THE 1990 - 2010

3.1 Impetus from lifeline studies

There was an increased focus on lifelines, such as roads, rail, water, electricity, gas, wastewater, ports and fuel since the Wellington engineering lifelines study (Centre for Advanced Engineering, 1991) in New Zealand. This study and other subsequent lifelines studies around New Zealand highlighted the vulnerabilities in our lifelines systems, and the need for action to ensure that they perform better. For network infrastructure, loss of life is not often a direct consequence, but performance is important. This led to a focus on performance, in the design of lifeline infrastructure. This led to a renewed focus on earthquake geotechnical engineering, because:

(a) There was need to better understand the spatially distributed earthquake geotechnical hazards, to better understand the effect of spatially distrusted infrastructure

(b) Lifeline infrastructure were affected by geotechnical conditions and required improve geotechnical earthquake engineering.

3.2 Earthquake geotechnical hazard mapping

The Resource Management Act 1991 placed a responsibility on local authorities to better understand, map and make available hazard information to assist in planning decisions. The RMA requirements, the Wellington engineering lifeline study, and the recognition of the significant earthquake hazard for New Zealand's capital city, led to the development of the first comprehensive earthquake – geotechnical hazard maps – fault rupture, ground shaking, liquefaction and earthquake induced slope failure hazards for Wellington (Wellington Regional Council, 1991, 1992,1993 and 1994; Brabhaharan et al, 1994), see Figure 4. This was followed by geotechnical earthquake hazard maps being developed for other regions of New Zealand. The development of geotechnical earthquake hazard mapping facilitated a better understanding of the resilience of lifeline infrastructure, the risk to the built environment and people (Works Consultancy Services, 1995) and land use planning (Brabhaharan 1998, 2000).

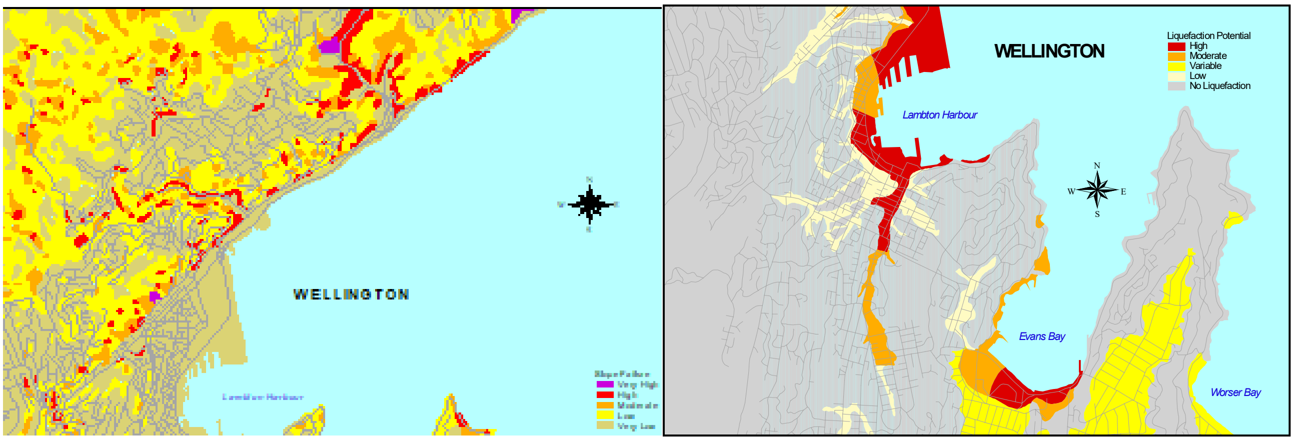

Figure 4: Earthquake induced slope failure and liquefaction hazard maps for parts of Wellington region

3.3 Design for liquefaction

The early 1990s also saw the adoption of geotechnical assessment for earthquake induced liquefaction, and consideration of options for ground improvement. An example is the Waipaoa water treatment plant in Gisborne (Brabhaharan and Vessey, 1992).

3.4 Earthquake design of retaining walls

Mononobe and Okabe (1929) proposed a method for the assessment of earthquake induced earth pressures on retaining walls and other structures. Wood and Elms (1990) prepared a report on earth retaining walls in the Road Research Unit Bulletin 84, building on the New Zealand research during the 1970s and 1980s, and proposed methods of design for retaining walls, based on whether they were flexible, stiff or rigid, see Figure 5. This was quickly adopted in the Ministry of Works – Works Consultancy Services (1990) retaining wall design manual and found its way into geotechnical engineering practice.

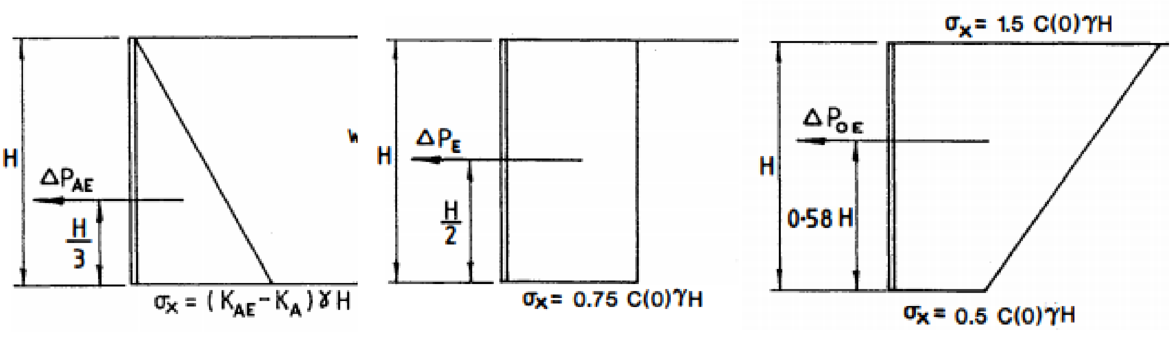

Figure 5: Earth pressures on retaining walls (L-R flexible – stiff – rigid walls) (after Wood and Elms, 1990)

3.5 Design of foundations and retaining walls

A more common application of geotechnical design of foundations and retaining walls was facilitated by the development and adoption of B1-VM4 (Department of Building and Housing, 199?), which provided an acceptable means of compliance under the New Zealand Building Code. This also allowed for use of earthquake earth pressures in the design of retaining walls (Pender, 1997).

3.6 Performance based design

The RRU Bulletin 84 also included assessment of the displacement of retaining walls based on the Newmark's sliding block model. Around the same period researchers such as Ambraseys and Menu (1995) published statistical analyses of the earthquake displacement of slopes based on the Newmark sliding block approach and past earthquake records. This provided a means of assessing the earthquake displacement with some level of statistical confidence. This background provided designers with the opportunity to design retaining walls to a set level of displacement performance rather than a design based on achieving a factor of safety. This led to early adoption of performance-based design in New Zealand geotechnical earthquake engineering practice, in the design of retaining walls.

During 1998-2001, a strategy was developed to assess the performance of Wellington city's road network and prioritise mitigation to enhance the earthquake performance of critical road corridors (Brabhaharan, 2004). This led to the implementation of a long-term programme of strengthening of vulnerable retaining walls and slopes. Appreciating that the performance of the roads was more important rather than achieving a target factor of safety, Brabhaharan and Saul (2005) adopted a performance-based design approach and limited displacement to an acceptable level. A performance-based design approach was also adopted for new transportation projects such as the Wellington inner city bypass, where Cut and prop underpass structures and soil nailed retaining walls were designed to limit displacement performance to an acceptable level rather than design for a factor of safety (Brabhaharan, 2007) as illustrated in Table 1.

Table 1: Seismic design performance criteria for soil nailed walls.

Location	Design peak ground acceleration	Performance criteria
Walls near bridge structures	0.68g	▪ Maximum displacement of the order of 100 mm ▪ Optimise design to further limit displacements to minimise damage to ensure continued functionality
Walls not near structures	0.59g	▪ Maximum displacement of the order of 200 mm

Note: after Brabhaharan, 2007

The displacement was limited to a level that would still allow performance of the highway, to allow continued functionality. The performance-based design approach also substantially reduced the construction cost for the project and led to significant savings.

3.7 New Zealand Bridge Manual

Transit New Zealand (subsequently became the NZ Transport Agency) developed a design manual for the design of bridges on state highways in New Zealand, and this also became a de facto standard for the design of bridges on other roads. This incorporated the seismic design of bridges, and the design standards were developed in line with international design practice and research. However, this did not incorporate the geotechnical design of bridge foundations and retaining walls. The Bridge Manual was developed in the early 2000s to include geotechnical design, including earthquake design, for foundations, retaining walls, embankments and slopes associated with highway structures (NZ Transport Agency, 2016).

The bridge manual facilitated the widespread use of the RRU Bulletin 84, liquefaction assessment and performance-based design of retaining walls, embankments and to a limited extent slopes, and helped embed these principles among the geotechnical practitioners. This was timely and has been used in the large programme of investment in transport infrastructure over the past 10 years.

4 CANTERBURY EARTHQUAKE SEQUENCE 2010-2011

The Canterbury earthquake sequence and in particular the Richter magnitude 7 Darfield earthquake of 4 September 2010, the Richter magnitude 6.3 Christchurch earthquake of 22 February 2011 and significant aftershocks caused significant damage to Christchurch city and surround regions, including 185 fatalities, predominantly from the collapse of two buildings in the central business district on 22 February 2011.

There are three significant observations from a geotechnical perspective

- Widespread liquefaction and lateral spreading along rivers in the CBD and towards the east, see Figure 6
- Rock fall in the Port Hills with significant run-out of larger boulders, see Figure 7
- Amplification of shaking in the low-lying soft areas as well as topographical amplification in the Port hills.

These phenomena contributed to the significant damage to residential properties, as well as liquefaction contributing to damage to commercial and high-rise buildings in the city and underground water, wastewater infrastructure. Transport generally performed better, although there was damage to bridges in areas of liquefaction, but where the ground was good the bridges performed well (Wood et al, 2012).

Figure 6: Liquefaction sand boils, ejection of sand and silt, and lateral spreading damage to transport

Liquefaction showed up shortcomings in planning and design practice for buildings and underground utilities. It showed that even recently constructed high rise buildings were founded on shallow foundations with little consideration of liquefaction, and ground improvement (where rarely used) did not perform satisfactorily. It also highlighted the deficiencies in land use planning where new subdivisions were constructed in areas highly susceptible to liquefaction and lateral spreading.

One of the key features of the earthquake sequence was that it raised the profile of liquefaction throughout New Zealand and that of geotechnical engineers, who were now accepted as critical to achieve resilience to earthquakes. The earthquakes also spurned a lot of research particularly into liquefaction and the behaviour of foundations on liquefiable ground.

Figure 7: Rockfall damage to houses and roads

5 DEVELOPMENTS SINCE THE CANTERBURY EARTHQUAKES

5.1 Royal Commission of Inquiry

The government appointed a Royal Commission to enquire into the Canterbury earthquakes, the loss of life and damage. The Royal Commission published a report recommending improvements in research, standards and practice. Although much of the focus was on buildings and structural engineering, it did make recommendations for improved geotechnical standards.

5.2 Investigation, information sharing, research and guidance

There has been significant investment in investigating the areas affected by the earthquake and making the information available through a national geotechnical database, from the government, through the Earthquake Commission and universities.

There has been significant effort to collate observations of liquefaction and measure the effects, and research is ongoing (Cubrinovski et al, 20xx, 20xx, and 20xx). One of key observations of value is on the magnitude of lateral spreading from liquefaction (Robinson et al, 2013), see Figure 8.

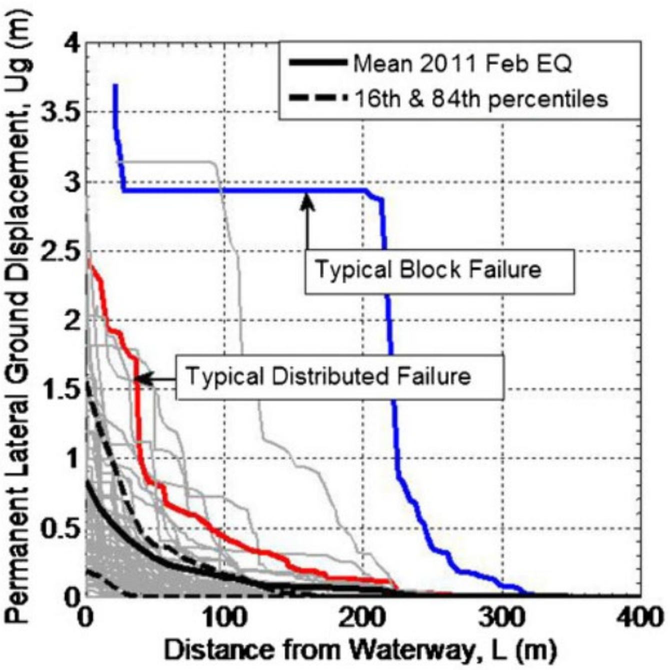

Figure 8: Liquefaction induced lateral spreading in the 2011 Christchurch earthquake 22 February 2011 (after Robinson et al 2013)

There has also been research and guidance on the underground utilities (Cubrinovski et al 2015 and Opus 2015). The NZ Transport Agency has also had research carried out on the design of bridge foundations on liquefiable ground (Opus, 2016).

Research into the performance of shallow foundations for residential and small-scale development has been carried out with funding from the Ministry of Business Innovation and Employment (2016) which provides advice for foundations on liquefiable ground.

One of the key developments since the Canterbury earthquake sequence is the development of modules to provide guidance for geotechnical earthquake engineering by the NZ Geotechnical Society and the MBIE, and includes the following modules:

- Module 1 – Overview of the guidelines
- Module 2 – Geotechnical investigations for earthquake engineering
- Module 3 – Identification, assessment and mitigation of liquefaction hazards
- Module 4 – Earthquake resistant foundation design
- Module 5 – Ground improvement of soils prone to liquefaction
- Module 6 – Earthquake resistant retaining wall design.

These modules are currently being reviewed and updated.

In addition to these modules for general practice, there have been developments in special practice areas, and these include:

- Upgrade of the New Zealand Bridge Manual, with enhancements in earthquake geotechnical guidance (NZ Transport agency, 2016) – this includes updated on the derivation of seismicity and a separate chapter for geotechnical design of highway structures.
- Analysis of piled bridges at sites prone to liquefaction and lateral spreading in New Zealand (Opus et al, 2018) – this presents a compilation of the approach for the seismic design of bridge foundations at sites prone to liquefaction.
- Seismic design and performance of high cut slopes (Brabhaharan et al, 2017) – this provides guidance for the assessment and design of high cut slopes for earthquakes, considering the location of slope failures and topographical amplification.

5.3 Land use planning

The Canterbury earthquake sequence also highlighted deficiencies in land use planning, with new residential subdivisions severely damaged by the earthquakes, predominantly due to liquefaction and lateral spreading. This led to an increased awareness among local authorities of the importance of land use planning, leading to significant changes to urban growth strategies, for example in Blenheim (Mason and Brabhaharan, 2013).

This also led to the compilation of guidance for land use planning for areas subject to liquefaction hazards (MfE, 2018).

6 KAIKOURA EARTHQUAKE 2016

A magnitude 7.8 earthquake struck the Kaikoura area in the north-eastern part of the South Island of New Zealand on 14 November 2016 at 12:02 am and caused widespread damage to the Kaikoura area and to the transport infrastructure along the Kaikoura coast.

The earthquake triggered thousands of landslides which led to the formation of landslide dams in the catchments and also damaged and blocked the South Island main trunk railway line and Stage Highway 1S, the main highway between Picton and Christchurch, see Figure 9. It took about 9 months to open access along the railway corridor and 13 months to open access along the state highway, and much longer to fully reinstate the transport corridors.

The earthquake created a heightened awareness among the public and government officials of the damaging effects of earthquake induced landslides. This led to a large programme of research into landslides funded by MBIE under the Endeavour programme, which is ongoing. Details of landslides triggered by the earthquake have been compiled and catalogued as part of this research (Massey et al, 2020).

One of the key observations from a resilience perspective from the Kaikoura earthquakes and the subsequent climatic events is that these smaller events can lead to considerable ongoing damage when the land is disturbed and loosened by earthquake shaking, and therefore seismic damage is not a one off event (Mason and Brabhaharan, 2019).

Figure 9: Landslides closed transportation corridors in the 2016 Kaikoura earthquake

7 RESILIENCE BASED DESIGN

7.1 Resilience concept

Geotechnical earthquake engineering approaches has continued to evolve in New Zealand from a factor of safety-based design for life safety to performance-based design and currently a resilience-based design approach (Brabhaharan, 2018).

Research into the resilience of transport networks and other lifeline infrastructure led to a greater understanding of the resilience of infrastructure (Brabhaharan et al, 2002), and characterisation diagrammatically as shown in Figure 10.

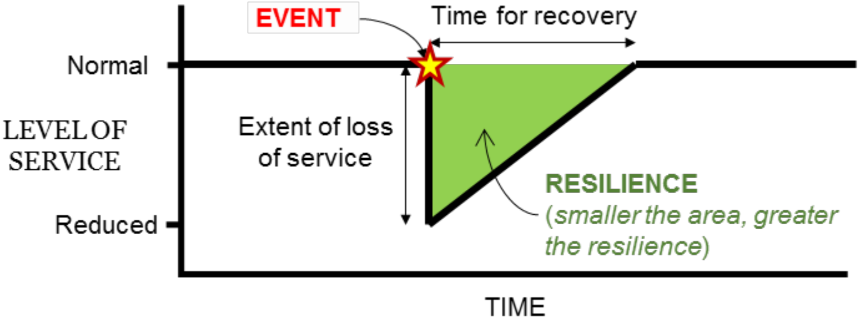

Figure 10: Concept of resilience for infrastructure (after Brabhaharan, 2004)

7.2 Focus on resilience

Insights from the resilience studies that followed highlighted the importance of resilience for the functionality of lifelines, and a better understanding of the seismic hazards including from local earthquakes such as the 2010-2011 Canterbury earthquake sequence and the 2016 Kaikoura earthquake indicated the need for a more rational approach to seismic design that would enable design to achieve a desired level of resilience rather than a factor of safety. This was important to achieve practical and economical designs in the areas of high seismicity in New Zealand, in particular.

Application to projects showed that desired levels of resilience could be achieved at no or a modest additional cost (Brabhaharan, 2009) using a resilience-based design approach, provided that there is a focus on resilience from early stages of projects, and throughout the life of project conceptualisation, development, design and construction. With this approach, limited damage and disruption would be acceptable provided that functionality can be quickly restored.

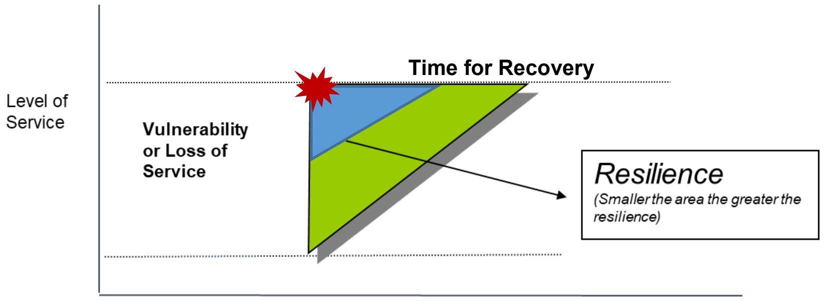

Figure 11: Resilience enhancement through reduced reduction and quick return to functionality

7.3 Design for hazard uncertainty

There is increasing recognition that there is significant uncertainty in the seismic hazard that is estimated and this changes as knowledge develops. It is important that this is taken into consideration in the design of our built environment, particularly infrastructure but also buildings. At the same time, it is important that such consideration does not make our infrastructure very expensive and unaffordable.

A resilience-based design approach with a focus on resilience would enable this to be considered. It is important that this is considered from early stages of site or route selection, conceiving design concepts and design, where solutions could be adopted which lead to increasing damage and reduction in functionality, but ensuring that functionality can be quickly restored. This also requires consideration of the hierarchy of needs to ensure critical components that are difficult and time consuming to restore are protected and some damage accepted for aspects that can be quickly restored.

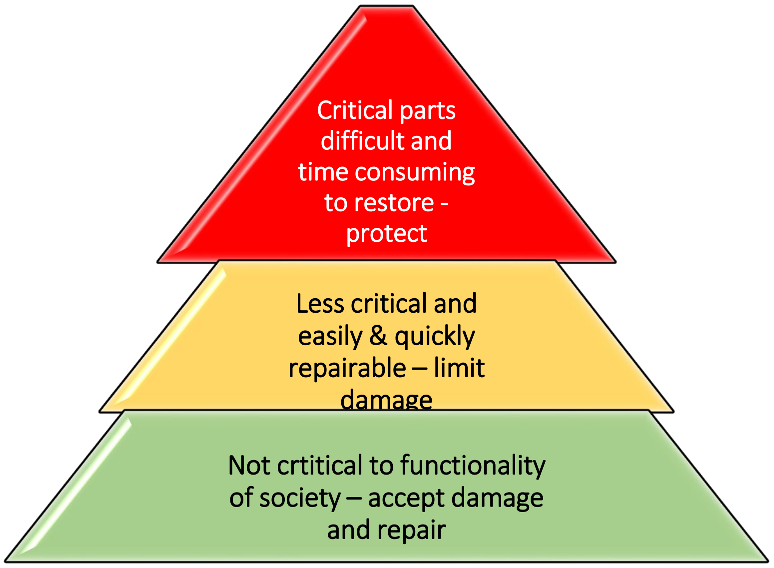

Figure 12: Heirarchy of needs for resilient design

8 SUSTAINABILITY

Increasing recognition of the criticality of climate change and actions to arrest global warming requires an urgent focus of sustainability. This is also imperative from a resilience perspective because climate change and extreme hazard events also lead to poor resilience from climatic hazards. Climatic events can also exacerbate seismic damage and risk particularly with respect to geotechnical hazards such as landslides and liquefaction.

Resilience based design makes good sense from a sustainability perspective, because:

- Concepts that are inherently resilient and able to be quickly restored are chosen
- Some damage is accepted and therefore resources are minimised
- Substantial damage and the resources and energy required for reconstruction is minimised or avoided.

In addition, it is important that we consider materials and techniques which minimise the use of energy and materials and construction methods with a large carbon footprint. An example is the use of reinforced soil retaining walls where the natural materials are reinforced rather that having to construct large structure to retain ground.

This then requires a focus on sustainability in design.

9 CONCLUSIONS

The paper shows the significant strides that have been made in geotechnical earthquake engineering practice over the past 30 years in New Zealand.

Recent large earthquakes have helped raise the awareness of earthquake geotechnical issues such as liquefaction and landslides, and this has helped in the uptake of good practice by the general practitioners as well as the community.

The earthquake geotechnical engineering practice has steadily developed over the past years, starting from a factor of safety-based design to a performance-based design, and now a resilience-based design as the resilience needs of our built environment is better understood. It is important that these concepts and principles are quickly disseminated and embedded into routine practice to benefit from the gains in development of these approaches.

Realisation of the criticality of climate change and impacts makes it important for our practice to embrace sustainability principles. A focus on resilience and resilience-based design makes good sense form a sustainability perspective, but we also need to focus on minimising energy and resource use in our designs. An early focus on resilience and sustainability would therefore be important in our future practice.

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