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Resilience based design in geotechnical engineering

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ABSTRACT

Resilience of our built environment is important for our societies faced with a range of natural hazards, anthropogenic hazards and climate change. This requires a fundamental rethink of our traditional established and codified design approaches. A focus on resilience is required from early stages of design processes, and a *resilience-based design* process would make a lot of sense.

Resilience is a function of robustness and an ability to rapidly return to functionality. After all functionality is why we build our built environment, whether it be infrastructure or buildings.

The paper illustrates how in geotechnical engineering, we have already been on a journey, gradually changing, at least in part, from a factor of safety-based design, displacement-based design, performance-based design of retaining walls and embankments, to recently a resilience-based design. A formal resilience-based design approach has recently been proposed for the seismic design of cut slopes. These changes have helped us to move progressively towards better performance and economical outcomes.

A resilience-based design is not just about the design approach but requires a holistic focus and change in the design process. The paper illustrates the evolution of the resilience-based design approach through some case studies such as the Transmission Gully expressway, Remutaka Hill highway realignment, and the Wellington East Girls College.

It also looks to the future and outlines a change in the process needed to focus on resilience at early stages and an integrated design process to help us achieve resilient infrastructure and buildings and ultimately resilient and sustainable communities.

1 INTRODUCTION

New Zealand's rugged terrain, high seismicity, severe climatic conditions, landslides and the potential for tsunami pose a significant risk to our built environment. Global warming and climate change are exacerbating the severity and frequency of climatic events.

Due to our history, our design standards have been shaped by those developed in more stable environments, and in past 85 years by concerns over life safety in earthquake events, particularly after the 1931 Napier earthquake. Consequently, our standards and codes largely focus on life safety, and on serviceability under live loads. New Zealand and other countries with developed earthquake design standards, have managed to minimise the collapse of buildings and associated loss of life in earthquakes through improved design practice, except in few instances. Now there is an increasing attention on the performance of our built environment in earthquakes and its ability to continue to function for the benefit of society.

There has been 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 and other lifelines studies that followed for our cities and districts highlighted the vulnerabilities in our lifelines systems, and the need for action to ensure that they perform better.

As our understanding of the importance of resilience increases, there is a need to focus on achieving resilience. This paper traces the development of displacement-based and performance-based design in geotechnical engineering and proposes a resilience-based design approach, where the focus of design is to achieve a desirable level of resilience, with a focus on geotechnical engineering.

2 PERFORMANCE BASED DESIGN IN GEOTECHNICAL ENGINEERING

The need for displacement-based design was increasingly recognised by geotechnical engineering practitioners since the early 1990s. New Zealand research into the earthquake performance of retaining walls during the 1970s and 1980s culminated in the publication of a summary of that research in the Road Research Unit Bulletin 84 (Wood and Elms, 1990), which proposed methods of design for retaining walls, classified as flexible, stiff or rigid. Importantly, this also included assessment of the displacement of retaining walls based on the Newmark's sliding block model. This was immediately adopted in the in-house design manual for retaining walls of Works Consultancy Services (1990) of the Works and Development Services Corporation (which was previously part of the Ministry of Works of New Zealand, now part of WSP). Together with statistical analyses of the earthquake displacement of slopes based on a collection of past earthquake records and the Newmark sliding block approach (Ambraseys and Menu, 1988), this provided a means of assessing earthquake displacement with some level of statistical confidence.

Publication by the Road Research Unit Bulletin and the adoption of this by Works Consultancy Services, together with the increased use of reinforced soil and soil nailed walls, which were well suited to design allowing displacement, led to a displacement-based design approach being adopted in geotechnical engineering. The increased focus on lifelines provided the opportunity for geotechnical designers to design retaining walls to desired levels of maximum displacement rather than a design based on achieving a factor of safety.

The development of a strategy for Wellington City Council, to assess and prioritise mitigation to enhance the performance of the city's road network (Brabhaharan, 2004), led to the implementation of a long-term programme to strengthen vulnerable sections of road – slopes, retaining walls, tunnels and bridges. Given the importance of performance of the roads, rather than achieving a factor of safety, Brabhaharan and Saul (2005) adopted a performance-based design approach in the strengthening of retaining walls and slopes, limiting displacements to an acceptable level (Table 1).

Table 1: Performance criteria for Ngaio Gorge road strengthening.

Performance level	**Performance**	**Return period**	**Peak ground acceleration**
Design level (NZ Bridge Manual)	No more than 150 mm wall displacement, with minor damage with cracking of road.	670 years	0.35g
Contingency Level (Characteristic M7.5 Wellington Fault earthquake)	No more than 450 mm wall displacement, leading to some repairable damage and extensive deformation of road acceptable, provided it is able to remain open to traffic.	-	0.47g

Limited displacement was accepted on the basis that the road will still allow emergency vehicles to pass, albeit slowly, and the cracking from displacement could be quickly remedied by using fill or bitumen to allow full access. Anchors for soldier pile walls were designed to be ductile to allow limited smaller displacements of the walls by using anchor bars with post-yield ductile behaviour.

This performance-based design approach was also adopted in geotechnical engineering since the mid-1990s in many new transportation projects, such as the Wellington Inner-City Bypass (Brabhaharan, 2007) as well as for the assessment of existing assets such as the Terrace Tunnel approach walls (O'Reily and Brabhaharan, 2006), see Figure 1.

Figure 1: Soil nailed walls - Wellington inner city bypass (left), Terrace tunnel approach walls (right)

This performance-based approach to geotechnical design was incorporated into the Bridge Manual for the design of highway structures in New Zealand (Brabhaharan, 2006). This performance-based design has now become a common established approach for the design of retaining walls, embankments and slopes in New Zealand.

3 DEFINING RESILIENCE

Resilience is the ability to continue to remain functional or rapidly return to functionality from adverse events. The need for a more systematic approach to manage risks led to research into strategies for the management of the risks to transportation networks from natural hazards in the period 2001-2006. The concept of resilience for road networks was developed, together with metrics to measure resilience (Brabhaharan, 2004). From the perspective of transportation networks, resilience is defined as the ability to recover quickly to restore the level of service after an event, which is shown conceptually in Figure 2.

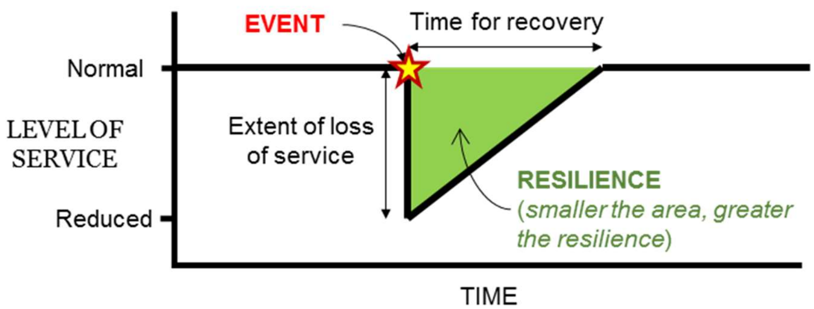

Figure 2: Concept of resilience for infrastructure and buildings (after Brabhaharan, 2004)

This is also applicable to other lifeline infrastructure and buildings which essentially exist to provide functionality or service to communities. Resilience for transportation routes were characterised by the metrics of availability state (that represents the reduced level of service) and outage state (that represents the time required to restore service). Similar metrics have been derived from this approach for other lifeline utilities and can also be used effectively for buildings.

4 INSIGHTS FROM TRANSPORTATION RESILIENCE STUDIES

Research into the systematic management of the resilience risk to transportation networks also led to the development of a spatial approach to assess the resilience of transport systems at a network-wide level (Brabhaharan, 2004). This led to network wide resilience studies for several individual road networks in the Wellington region as well as elsewhere (Brabhaharan, 2010).

In the Wellington Region, individual resilience risk studies culminated in a region-wide integration of network resilience assessments in the Wellington Region through collaboration between the NZ Transport Agency, the 5 local authorities of Upper Hutt, Lower Hutt, Wellington, Porirua and Kapiti Coast, and Opus (Brabhaharan and Mason, 2012), see Figure 3. In 2016, the Wellington region's resilience studies were extended to include storm resilience across the region (excluding the Wairarapa) and the impact of building damage and collapse (during earthquakes) on transport access in the inner-city areas of Wellington (Opus, 2017).

Transportation access between districts in the region and access into and out of the Wellington region is likely to be closed for a long period of several months in the event of a large earthquake in the region, jeopardizing response and recovery after the event. The integrated regional resilience study highlighted the critical importance of transport resilience to the survival and functionality of society.

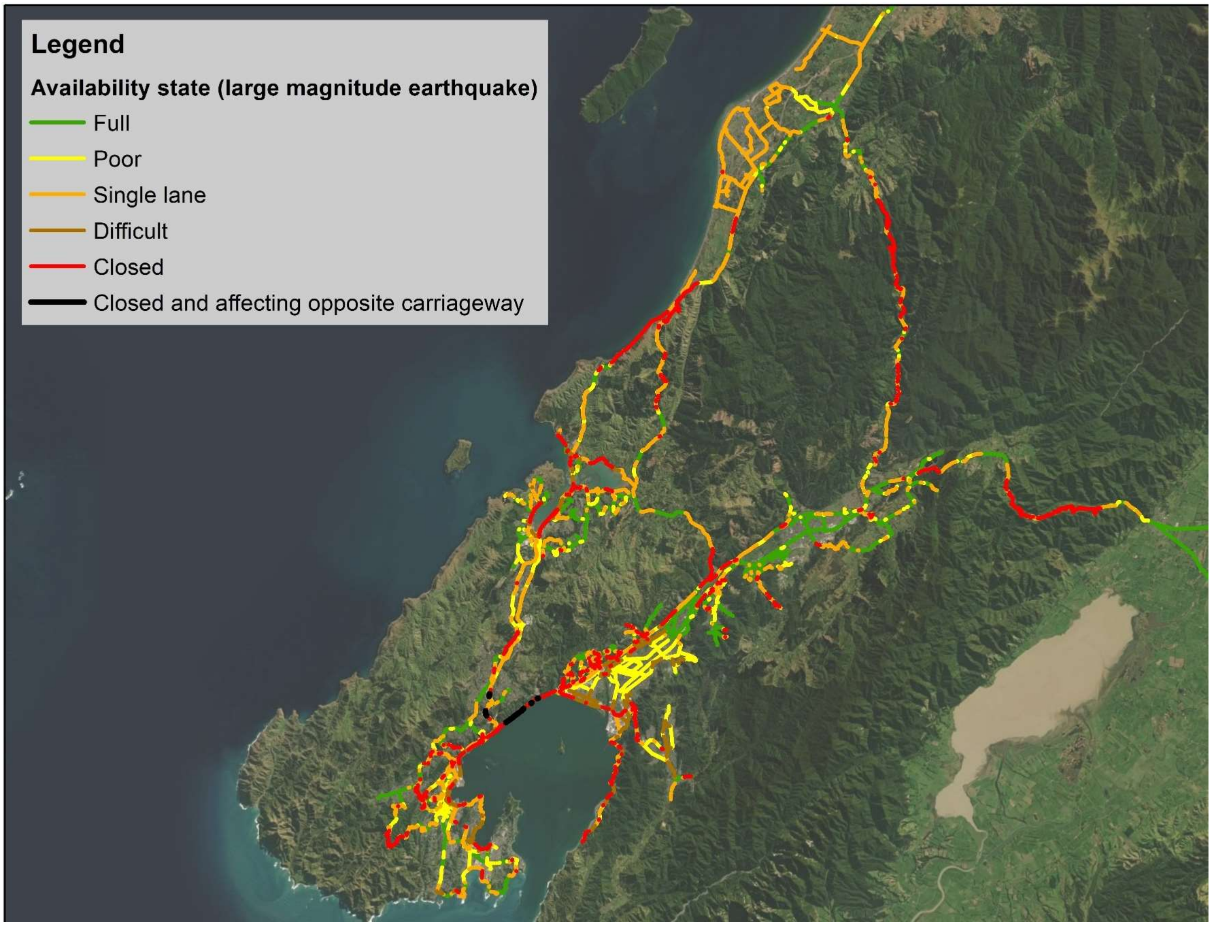

Figure 3. Resilience of Wellington road transport network in a local large earthquake event.

Given the terrain, seismicity and climatic conditions in New Zealand, many of our regional transportation networks including Wellington, lack redundancy in transport corridors. This understanding of the lack of resilience of the transport links and the lack of redundancy in the transport system in the Wellington region has led to a realisation that existing infrastructure assets have resilience issues that need to be addressed. This was critical to bringing a focus on resilience in conceiving and designing new infrastructure. Such focus will help enhance the overall resilience of transportation in the region.

More generally, the resilience expectations can be significantly different depending on the resilience context of the asset in the region. Lifeline systems with very little redundancy will require a greater level of robustness (for example in Wellington) compared to networks where there is abundant redundancy (for example transport routes in Christchurch). This will apply both to existing lifeline infrastructure as well as new infrastructure, including buildings. Therefore, it would be prudent to consider the resilience context and associated resilience expectations in the design of infrastructure.

This raises the question as to whether we should be using resilience as a basis for our design, as well as asset management of our built environment including buildings and infrastructure.

5 LESSONS FROM PAST EVENTS

5.1 Observations in past events

Past natural hazard events have enabled engineers to observe, learn and understand the resilience implications and needs for engineered systems. Such events have provided a valuable opportunity to understand the resilience implications, as well as test and calibrate resilience studies. The 2009 Wenchuan earthquake in China (Yu et al, 2009), the 2010-2011 Canterbury earthquake sequence (Wood et.al, 2012; Brabhaharan, 2011, 2012), the 2016 Kumamoto earthquake in Japan (Chiaro et al, 2017) and the 2016 Kaikōura earthquake in New Zealand (Mason and Brabhaharan, 2019, 2020), as well as many storm events enabled the author to observe and learn from these events. The observations also illustrate the geotechnical nature of many resilience issues.

5.2 The 2016 Kaikōura earthquake

The 14 November 2016 magnitude 7.8 Kaikōura earthquake in the upper South Island of New Zealand caused failures along the transportation corridor between Picton and Christchurch. Some observations to understand the resilience of our transport network, and the implications for response and recovery were made from that event:

- Both rail and road access (South Island main trunk railway line and State Highway 1S) was closed by the earthquake between Ward and Cheviot for 9 and 13 months respectively;
- Road access was restored quickly in places where there were small to moderate size failures, with limited repair and disruption costs;
- It took over a year to restore limited access where closed by large landslides, see Figure 4.
- The restoration of limited access by clearing and stabilizing large landslides involved very large costs and the disruption of a nationally significant transport corridor.

Figure 4: National transport corridor closed by large landslides in the 2016 Kaikōura earthquake

It should be noted that the damage was predominantly of a geotechnical nature with large landslides, rockfall, embankment failure, liquefaction and settlement of bridge abutments. The transport routes were further affected by damage from storm events following the earthquake. The earthquake-displaced or loosened hillsides failed, and debris flows from relatively modest storm events caused further disruption to transportation access and recovery efforts. This highlights the need to consider resilience in geotechnical engineering practice, so that more resilient infrastructure can be developed over time.

5.3 The 2019 West coast storm event

In New Zealand, storm events regularly cause extensive damage and closure of transportation routes, as well as damage to other infrastructure and buildings. For example, the March 2019 storm closed the state highway between Greymouth and Franz Joseph causing collapse of the bridge across the Waiho River and many landslides, see Figure 5.

Figure 5: State highway closed by landslides and bridge collapse in the March 2019 storm event

These impact on infrastructure in frequent storms, and the increasing frequency and severity of events due to climate change highlight the need to consider resilience in our engineering practice.

6 GEOTECHNICAL DESIGN OF INFRASTRUCTURE FOR RESILIENCE

6.1 Case Study 1 – Transmission Gully expressway

Wellington's transportation network has poor resilience (as discussed earlier), and the resilience issues arise predominantly from fault rupture, landslides and liquefaction – all significant geotechnical challenges. Therefore, there was a critical need for measures to enhance the resilience of the transport network, and geotechnical engineering needed to play a significant role in this response. This understanding of the resilience context led to an early focus on resilience during the development of an alternate Transmission Gully route north of Wellington in the 2007 to 2011 period. The early focus on resilience enabled the development of a scheme with a preliminary design that provided a greater resilience, in this case, at a lower cost (Brabhaharan, 2009).

The early resilience focus during conceptual design included challenging and modifying the route alignment and road form to enhance resilience. For example, making changes so that the inevitable crossing of a major active earthquake fault (the Ohariu Fault) was on earth embankments rather than on viaducts as had been previously proposed. While both embankments and viaducts would be damaged by rupture of the fault, an embankment can be quickly restored by earthmoving machinery to provide limited access, reducing the outage time to within a few days, compared to a viaduct, which would take many months to years to restore. The benefits of such an approach was apparent during a subsequent reconnaissance visit to China after the 2009 Wenchan earthquake (Yu et al, 2009), when it was observed that a bridge destroyed by fault rupture remained cut-off six months after the event, whereas a road embankment cut-off by fault rupture had been restored to provide temporary access within days where, see Figure 6.

Observations in the Wenchuan earthquake also highlighted the vulnerability of bridges adjacent to steep slopes to landslides, and many bridges alongside steep slopes or cuttings had been proposed in the early Transmission Gully scheme, see Figure 7. The road form was improved in 2010-2011 by avoiding viaducts or half-bridges at the base of steep slopes or cuttings that are vulnerable to landslides in earthquakes and replacing them with reinforced soil embankments. While both bridges and reinforced soil embankments will be closed by debris inundation from landslides, the debris on the embankments can be quickly cleared, whereas collapse of bridges due to landslides will take months to years to replace.

Figure 6: Bridge destroyed by fault rupture remains cut off after six months (left), road embankment affected by fault rupture quickly restored within days (right) after the 2008 Wenchuan earthquake in China

Figure 7: Bridge destroyed by landslides in the 2008 Wenchuan earthquake China (left), early Transmission Gully scheme with bridges near steep slopes and cuttings (right)

The quicker recovery possible after an earthquake with an embankment form to replace viaducts and bridges subject to fault rupture or landslides, as well as modifications made to cut slopes to accept small failures that can be quickly cleared, but avoid large landslides that will close the route for long, meant a much greater resilience could be infused in the scheme design for the expressway.

This case study illustrates how a focus on the twin metrics of resilience – functionality and time for recovery – helped achieve a more resilient scheme design solution developed for the expressway in 2007-2011. In contrast, the previous traditional design based on margins of safety, with little consideration of resilience, led to a simple selection of a route based on bridges and earthworks cut-fill balance and poor resilience. The changes also resulted in much lower costs (a saving of about $ 300 Million on the $ 1 billion scheme) due to the change from viaducts to embankments, and acceptance of damage where access can be quickly restored (Brabhaharan, 2009).

Reflecting on this case study, the learnings can be made:

- Significant enhancements in resilience can be achieved, if there was a focus on design for resilience from early stages of projects and cannot be achieved easily once the alignments and road forms are decided.
- Achievement of significant improvements in resilience does not necessarily have to cost more if there was an early focus on resilience.

There is a need to maintain this focus on resilience throughout project development stages and construction, or else benefits gained could be eroded through procurement and detailed design.

6.2 Case study 2 – State highway 2 Muldoon's corner realignment

The upgrade of the Muldoon's Corner section of SH2 in the Remutaka Hill Range in 2010-2012, see Figure 8, also was designed with a focus on resilience. The highway is in rugged mountainous terrain, and the original design proposed large cut slopes, bridges and sidling fill embankments. An early review of the design with a focus on resilience enabled changes to be made to the alignment to avoid sidling fill embankments which are prone to failure and instead use of full embankments and where necessary reinforced soil embankments (Brabhaharan and Stewart, 2015). The bridges were also eliminated because bridges close to high slopes and cuttings are vulnerable to failure due to landslides, as observed in the 2008 Wenchuan earthquake in China (Yu et al, 2009), and would take a long time to reinstate.

Figure 8: State highway 2 Muldoon's corner realignment on the Remutaka Hill Road, north of Wellington

The cut slopes formed through rock (see Figure 8), considered the defects in the rock mass and their orientations were determined through acoustic televiewer surveys in boreholes as well as traditional mapping of rock exposures. A focus on resilience during the design stages led to the rock cuttings being designed to accept small wedge type failures that can be cleared quickly or contained by rock fall barriers but to avoid large landslides along outward dipping defect planes by adopting suitable cut slope angles. Along one section, the rock slopes were stabilised with high capacity rock anchors to enhance stability, particularly in storm and earthquake events, and avoid large failures that could close the route for long periods of time.

This focus on resilience during design, resulted not only in greater resilience, but also acceptable costs of construction, which were lower because of the elimination of bridges. This case study highlights the need to maintain the early focus on resilience through design and construction.

6.3 Case study 3 – Wellington East Girls College redevelopment

A seismic assessment of the buildings and facilities as part of the master planning for the school identified a number of vulnerabilities associated with the school. This included the following geotechnical resilience risks to the school in the event of a significant earthquake in Wellington (Gkeli and Brabhaharan, 2016), see Figure 9:

- Failure of steep rock cut slopes behind the buildings, which could severely damage buildings very close to the cut slope and prevent egress from the buildings by debris blocking the escape routes in a fire following the earthquake. This would not only pose a direct risk to the building but also affect the functionality and safe egress.
- Failure of slopes and retaining walls supporting the car parking structure and driveway access to the rear of the school, and potentially affecting Block 2.

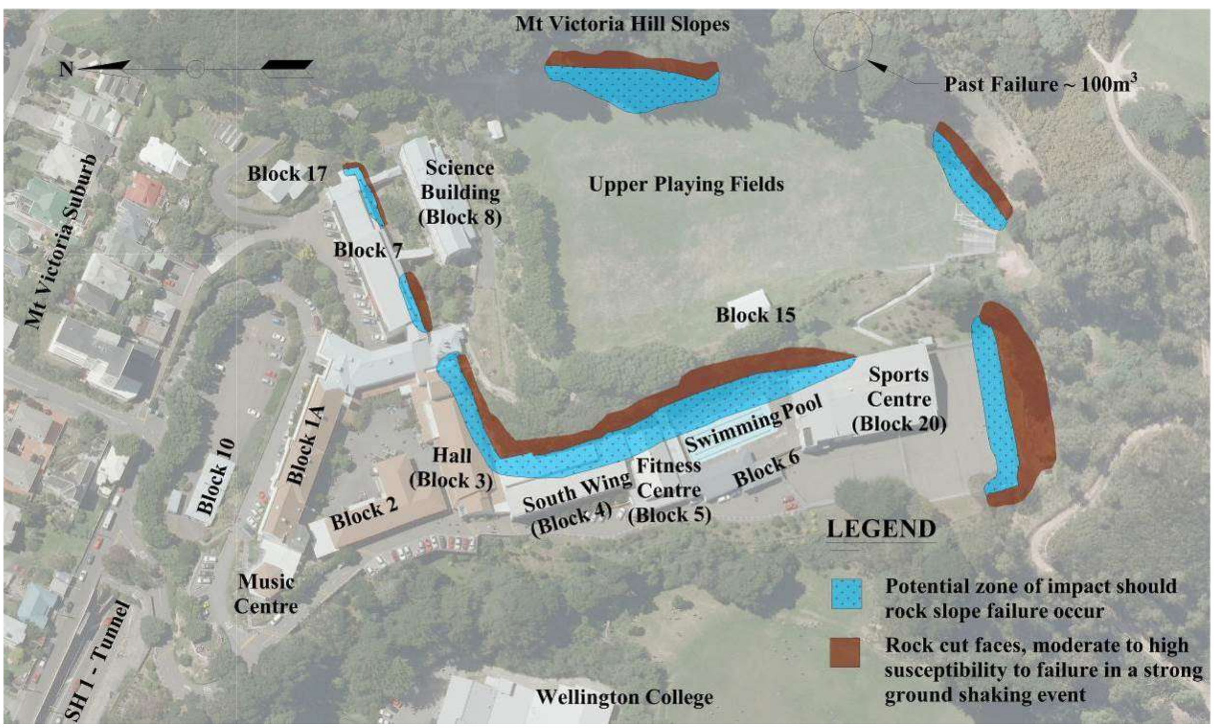

Figure 9: Wellington East Girls College resilience risks

A focus on the resilience of the school, led to geotechnical engineering measures involving the reprofiling the cut slopes on the eastern side of the school buildings to more stable angles, stabilisation of some sections with rock bolts and netting, and erection of a safety barrier to ensure functionality of the school including safe egress in the event of fires. The fill from this reprofiling was used to buttress the slopes and retaining walls on the western side of the school buildings and driveway but accepting some displacement of the buttress and associated cracking and deformation of the access, but not loss of access and functionality. This ensured that the school would have adequate post-earthquake functionality and egress routes. The work was carried out in conjunction with master planning to cater for roll growth at the school, and together with major reconstruction of vulnerable buildings to provide improved capacity, functionality and seismic safety.

This case study shows that focus on resilience enabled the school to achieve greater resilience and post-earthquake functionality at a modest cost, and resilience focussed design can also be used to enhance resilience in the buildings sector.

7 RESILIENCE BASED DESIGN IN GEOTECHNICAL ENGINEERING

7.1 Key principles

The key principle of resilience-based design is to enable continued or quick return to functionality of the building or infrastructure. This design approach for infrastructure and buildings based on resilience can be illustrated conceptually using the diagram in Figure 10.

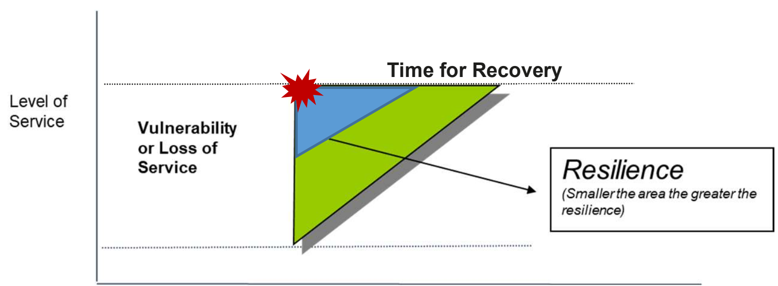

Figure 10: Resilience enhancement through reduced reduction and quick return to functionality

A resilience-based design approach involves adopting a design that helps improve resilience by limiting the reduction in functionality in an adverse event and enabling quick restoration of service (blue triangle compared to the green triangle). This approach would help achieve a desired post-event return to functionality at an optimum cost. Such an approach has evolved through use of this philosophy on several projects as illustrated through the case studies above, and parallel research.

A resilience-based design can be applied to a broad range of infrastructure and buildings in the wider built environment, more than the range of case studies discussed above.

7.2 Requirements in a resilience-based design approach

Resilience also needs to be cognisant of the needs of society in different levels of events, such as:

- In high frequency but lower impact events such as a storm, continued socio-economic functionality is important for society, and infrastructure systems need to be able to function to the fullest extent possible with quick restoration of functionality with capacity.

- In lower frequency, and higher impact events such as a major earthquake (eg. Christchurch February 2011), the socio-economy will be less functional, and services for emergency response and survival will be critical, followed by quick restoration of functionality in the days to weeks to allow return to socio-economic functionality.

These different dimensions of the functionality needed by society need to be taken into consideration in resilience-based designs.

A resilience-based design approach would require:

- Understanding the resilience context, and the needs or expectations of different infrastructure and their components, depending on criticality and exposure. This includes understanding any inter-dependence between infrastructure networks.
- Design that provides the necessary level of functionality and time for recovery, depending on the identified criticality and resilience expectations.
- Focus on the hierarchy of actions of resilience-based design as outlined below.

7.3 Hierarchy of actions in resilience-based design

In an engineering system, it is also important to consider the hierarchy of components to achieve the required level of resilience in a cost-effective manner. This would enable focus on the most critical parts of the system. Figure 11 shows the key features of characterising components based on their ability to be restored quickly and efficiently, in a resilience-based design.

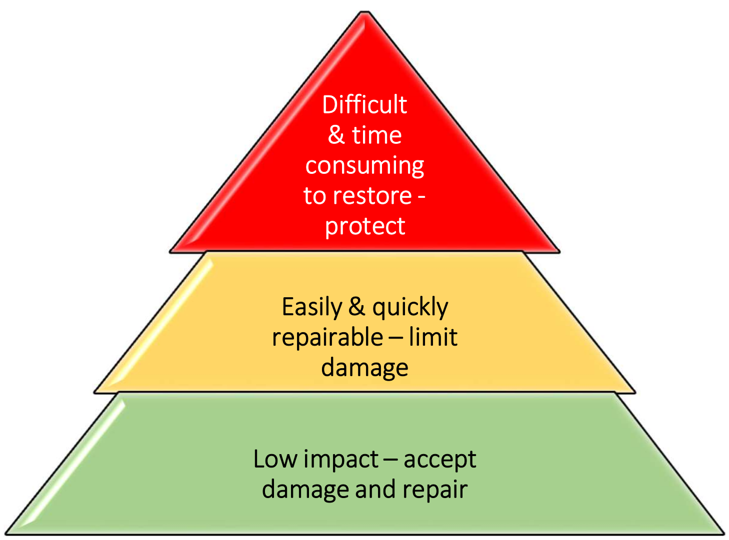

Figure 11: Hierarchy of needs for a resilience-based design

Such a hierarchy will facilitate appropriate focus and actions in the resilience-based design:

a) Difficult – costly – time consuming to repair components . . . minimize damage (eg. bridges providing access, trunk utilities sharing transport corridor)

b) Easily - quickly repairable parts . . . accept limited repairable damage (eg. distributor pipes)

c) Low impact on community functionality – low cost . . . accept damage (eg. low importance roads where communities will still have critical services)

d) Systems and components are flexible and ductile (eg. non-brittle retaining walls, flexible or ductile pipes, embankments that can displace)

e) Infrastructure can perform in a ductile manner albeit with greater damage and is able to be restored in events somewhat greater than the design level.

7.4 Guidance for seismic design of high cut slopes

Given the lack of guidance for the seismic design of cut slopes in engineering practice, Brabhaharan et al (2017) proposed, carried out and reported on research for the New Zealand Transport Agency. One of the key recommendations from this research was to use a resilience-based design approach for the design of high cut slopes. The framework developed proposed the following approach:

- Selection of an Importance Level Category based on NZS 1170.5 (Standards New Zealand, 2004) and the Bridge Manual (NZ Transport Agency, 2016).
- Selection of a Resilience Importance Category based on the resilience context of the route where the cut slope is located.
- Use of a Design Approach based on the importance level and the Resilience Importance Category, size of cut slopes, complexity of geotechnical conditions and functionality.
- Development of performance criteria based on the resilience context, criticality and expected performance.

It also provided guidance for the selection of peak ground accelerations, including topographical effects, and critical failure mechanisms in earthquakes.

7.5 Resilience based design in geotechnical engineering

A formal resilience-based design approach has been proposed for the first time in the high cut slope design guidance, although this has developed progressively over 20 years as shown in the case studies.

The ground is inherently variable and poses significant risks to associated buildings and infrastructure when exposed to natural hazard events. Therefore, geotechnical engineering has lent itself well to the development of the resilience-based design approach. However, this requires considering the infrastructure holistically with other disciplines to effect resilience-based design. Although the development of resilience-based design for geotechnical engineering has been the focus of this paper, resilience-based design is also applicable for other engineering disciplines in the design of buildings and infrastructure.

8 CONCLUSIONS

Design of lifeline infrastructure for earthquakes has evolved from a purely margin of safety-based design, to a performance-based design, and the now proposed resilience-based design over the past 25 years. Resilience based design will help focus our attention to both functionality and time for recovery and facilitate the achievement of enhanced resilience for our infrastructure and buildings in a cost-effective manner.

Geotechnical engineering deals with significant uncertainty of performance and the impacts of natural hazards risks to our built environment. It is therefore natural that performance-based design and now resilience-based design has evolved in geotechnical practice. However, for an effective resilience-based design, it is vital to consider the infrastructure system holistically and for all the allied disciplines to work together.

Our focus needs to be on achieving continued functionality of society albeit at reduced levels and facilitate quick recovery after natural hazards such as storms and earthquakes. There is a need to embed resilience-based design in our practice. A resilience-based design approach is critical to enable us to work towards a more resilient built environment, and for a more resilient society. It is important that we embrace this approach and put in place measures to implement this in practice, including embedding it in our policies, standards, guidance and procurement processes.

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