EVOLUTION OF RESILIENCE-BASED DESIGN OF INFRASTRUCTURE

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Abstract

Ensuring good earthquake performance while achieving economical design requires a focus on resilience rather than purely margins of safety. In response design of infrastructure has evolved from a margin of safety approach through performance-based design to a resilience-based design focus.

Performance based design of retaining walls was introduced into the design requirements of the Bridge Manual (Brabhaharan, 2006) following use for the strengthening of walls for earthquake performance. It specified a transparent approach where the full earthquake loads were considered, and the focus was on an acceptable level of displacement that does not compromise performance. This led to familiarity of practitioners with performance-based design.

A new resilience-based approach is being evolved to ensure that design can accommodate greater than code or multiple earthquakes, albeit with limited damage that does not severely compromise performance. Design should also cater for controlled displacement or deformation that may exceed design criteria, but still provide for resilience of infrastructure facilities. Principles of resilience for design considers not only the performance of the asset but the ability to recover quickly to provide functionality. This requires greater protection for difficult to repair components of a system, limiting damage to easily repairable important parts and allow damage and plan for recovery of aspects which are not important for the community to function. Guidelines have recently been developed for a new resilience-based design approach for cut slopes, and by extension to transportation routes.

The paper illustrates the evolution of performance based and resilience-based design approaches through examples from the author's experience.

Introduction

Earthquake engineering has evolved over the years as engineers have learnt from the consequences of past earthquakes. Engineering for earthquakes in New Zealand has evolved over the past 85 years or more, particularly since the 1931 Napier earthquake.

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. In countries with more developed earthquake design standards, collapse of buildings and associated loss of life in earthquakes has been limited by design practice. Now there is an increasing attention on the performance of our built environment in earthquakes and their ability to continue to function for the benefit of society.

In New Zealand, 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). This and other lifelines studies that followed for cities and districts 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 the performance, in the design of lifeline infrastructure. As our understanding of the importance of resilience increases, there is a need to focus on *design for resilience*.

Performance Based Design

There was an early adoption of performance-based design in New Zealand, in the design of retaining walls. The Road Research Unit Bulletin 84 (Wood and Elms, 1990) summarised research into the earthquake performance of retaining walls during the 1970s and 1980s in New Zealand, and proposed methods of design for retaining walls, based on whether they were flexible, stiff or rigid. It 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.

During 1998-2001, Opus International Consultants developed a strategy for Wellington City Council to assess the performance of their road network and prioritise mitigation to enhance the earthquake performance of critical road corridors. 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, see Table 1.

Table 1. Performance Criteria for Ngaio Gorge Road Strengthening

Performance Level	*Performance*	*Return Period*	*Peak Ground Acceleration for Design*
Design level (New Zealand Bridge Manual)	No more than minor damage with cracking of road not exceeding 150 mm	670 years	0.35g
Contingency Level (M7.5 Wellington Fault earthquake)	Some damage requiring repairs and extensive deformation of road is acceptable, but road should be able to remain open to traffic.	-	0.47g

Notes: after Brabhaharan and Saul (2005).

Displacement of the wall was limited to 150 mm in a design level event (670-year recurrence interval based on the New Zealand Bridge Manual at the time), and larger displacements (not exceeding 450 mm) in a characteristic Magnitude 7.5 Wellington Fault earthquake event, to ensure that the road will remain open albeit with some damage. This was on the basis that some displacement of the road will still allow emergency vehicles and other vehicles to pass, albeit slowly, and cracking from road displacement could be quickly remedied by using fill or bitumen to allow full access. Anchors were designed to be ductile and allow displacement by post-yield ductile performance of the bars.

This performance-based design approach enabled the development of cost effective solutions to enhance earthquake performance and hence enabled such strengthening works to proceed, examples of which are shown in Figure 1. The expected performance of existing retaining walls and infrastructure in earthquakes was assessed using a similar performance-based approach (O'Reily and Brabhaharan, 2006).

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

Figure 1. Strengthening of Ngaio Gorge retaining walls (left), Terrace tunnel approach walls (right).

Resilience

In 2001-2006, New Zealand research into strategies to manage the natural hazards risks to road networks led to the development of the concept of resilience for roads, together with metrics to measure resilience (Brabhaharan, 2004).

For transportation networks (as well as similar lifeline infrastructure), resilience is the ability to recover quickly and restore the level of service, which is illustrated conceptually in Figure 2. This can be characterised by the metrics of *availability state* and *outage state* for transportation infrastructure. And a similar framework has since been used for other lifeline infrastructure.

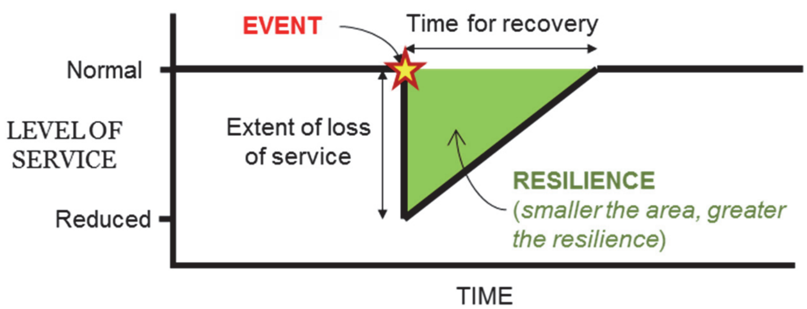

Figure 2. Concept of Resilience for lifeline infrastructure.

Transportation network wide resilience studies have led to a realization that existing infrastructure assets have resilience issues that need to be addressed, and resilience expectations can be significantly different depending on the resilience context of the road link or asset. By extension, new infrastructure will also have different resilience expectations depending on the network context of the asset. For example, new infrastructure on a route with very little redundancy and poor resilience of existing assets, will require a greater level of resilience than similar infrastructure at a location where there is plenty of redundancy.

Wellington Regional Road Network Resilience

The network wide assessment of resilience using a geospatial platform developed by Brabhaharan (2004) enabled the assessment of the resilience of several lifeline networks. Resilience studies for Wellington Region's road networks over the preceding decade led to an integrated region-wide resilience assessment (Mason and Brabhaharan, 2013) and highlighted the critical vulnerabilities in the road transport network, see Figure 3.

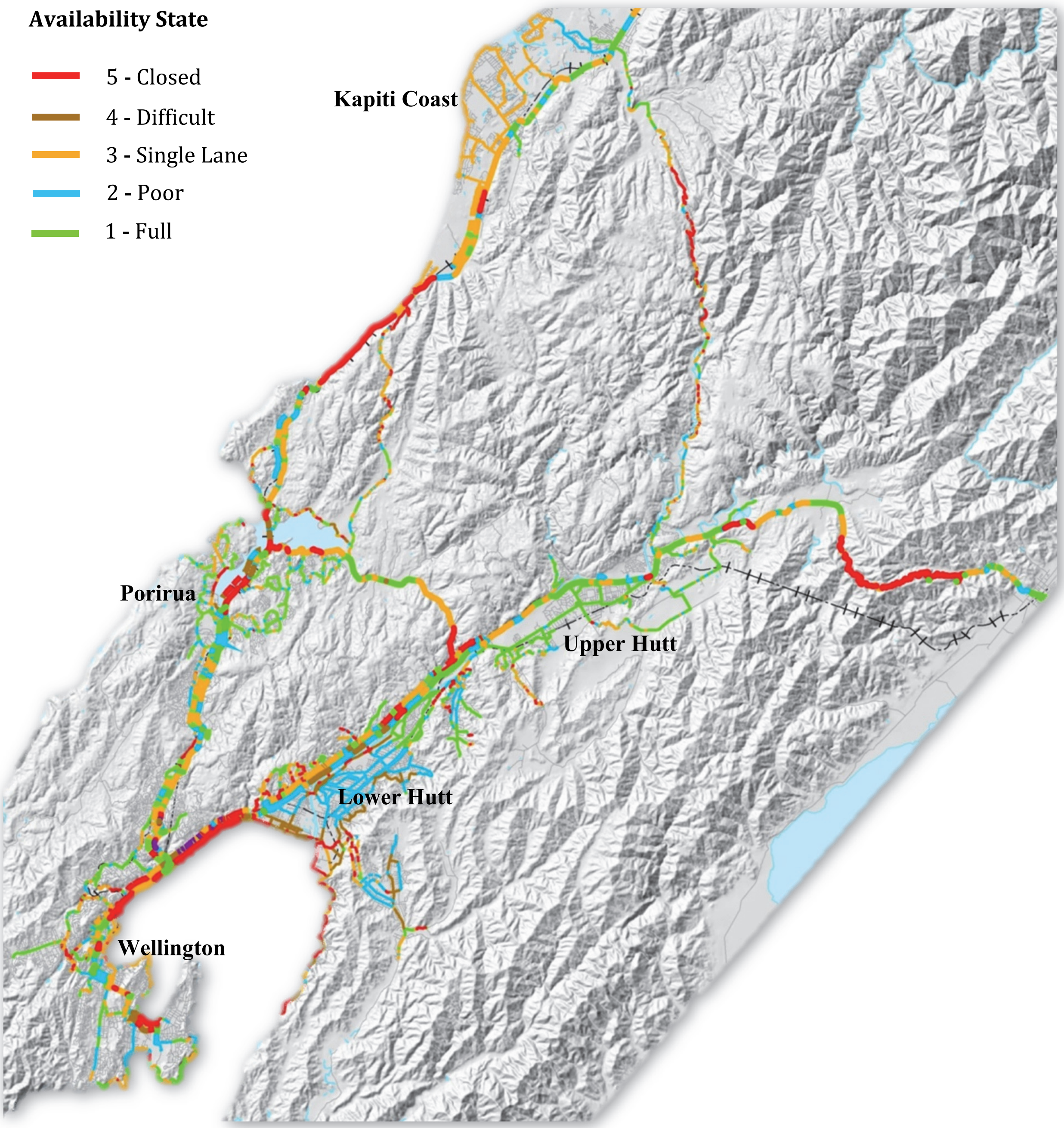

Figure 3. Resilience of Wellington road transport network in a local large earthquake event.

Figure 3 shows that access in and out of the region as well as between districts and cities within the region will be closed in the event of a large earthquake in the region, and that these closures are expected to be for several months, jeopardizing response and recovery after the event. This study highlighted the critical importance of resilience to the survival and functionality of society in the aftermath of a large earthquake. Given the terrain, seismicity and climatic conditions, many of our regional transportation networks lack redundancy in transport corridors and hence such criticality is not uncommon.

Importance of Early Focus on Resilience

A case study of the conceptual design of the Transmission Gully expressway showed that an early focus on resilience can help achieve greater resilience of lifeline infrastructure at no additional cost (Brabhaharan, 2009). This case involved modifying the route alignment and road form to cross a major active earthquake fault on unreinforced soil embankments and reinforced soil embankments rather than the viaducts previously proposed. Though both embankments and viaducts will be damaged by rupture of the fault, an embankment can be quickly restored by earthmoving machinery reducing outage time to within a few days, compared to a viaduct, which will take many months to years to restore. This meant a much greater resilience of the route, and in this case also resulted in much lower costs due to the change from viaducts to embankments. Such significant enhancements in resilience at no additional cost would be difficult unless there was a focus on design for resilience from early stages of projects.

Designing for Resilience

Transportation projects to form or improve roads through rugged terrain are a challenge from a resilience perspective. The active tectonic environment and associated steep rugged slopes and tectonically deformed and fractured rocks with defects mean that steep cut slopes to form roads lead to poor performance in hazard events such as earthquakes. Therefore, flatter slopes and extensive stabilisation measures are required, with associated large costs.

Achieving resilience requires a focus on reducing one or both of the two metrics of resilience:

- Loss or reduction in service or functionality
- Time for recovery.

Often the focus is on achieving margins of safety rather than service and functionality or time for recovery. A holistic approach would help achieve greater resilience at a more modest and affordable cost. For example, the design of cut slopes then requires:

- accepting failures (such as small to moderate size wedges) in an earthquake, where road access can be quickly restored by cleaning up the debris; and
- avoiding large failures that are likely to close the highway and take a long time to restore access.

This can be illustrated through observations of failures in the 2016 Kaikoura earthquake along State Highway 1S between Picton and Christchurch, where:

- road access was restored quickly in places where there were small to moderate size failures, with limited repair and disruption costs; but
- it took a year to restore limited access where there were larger landslides, see Figure 4. The restoration of limited access by clearing and stabilizing large landslides involved very large costs and the disruption due to a one-year closure led to major disruption costs to the economy.

Figure 4. Landslides in the 2016 Kaikoura earthquake, New Zealand.

This principle of resilience considering loss of access and the outage period has been adopted in the strategy for enhancing the resilience of roads in Wellington City discussed above. Vulnerable retaining walls and steep under-slopes that have the potential to remove the road platform in a natural hazard event such as an earthquake or large storm, and which will take many weeks to months to restore have been prioritized for strengthening to enhance resilience, as illustrated in Figure 1. Low to moderate height uphill slopes are susceptible to failure and could close the road, but access could be restored quickly by earthmoving machinery, and hence have a lower priority for strengthening, and could be managed by emergency response planning.

Resilience based Design

Focus on resilience for design of infrastructure can be illustrated from the resilience diagram in Figure 5.

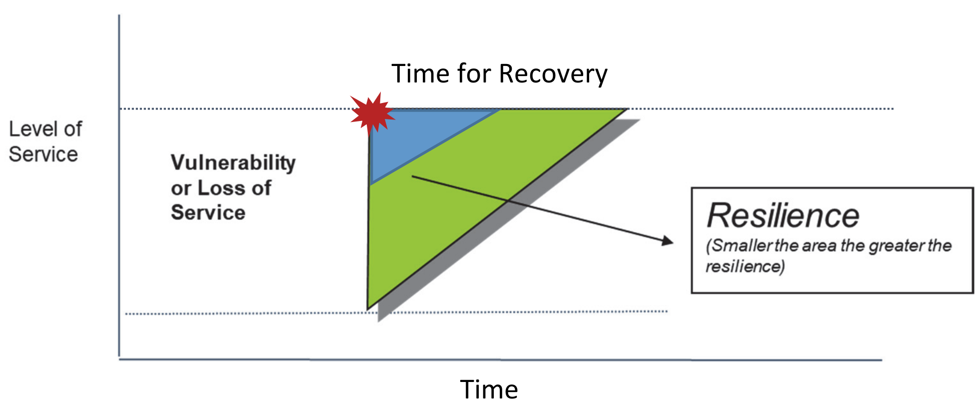

Figure 5. Enhancing Resilience through reduced reduction in functionality and time for recovery.

Resilience can be enhanced by limiting the reduction in service or functionality in an earthquake or other event, as well as adopting a design that enables functionality to be quickly restored (blue triangle). Such an approach to design will help achieve the required post-earthquake return to functionality at an optimum cost.

The need for resilience-based design comes from the realisation of:

- the critical importance of resilience for lifeline infrastructure
- the importance of considering resilience holistically – functionality, time for recovery and damage
- the focus needed on resilience from an early stage of design
- the need for targeted use of scarce resources to achieve the necessary resilience outcomes
- the fact that resilience does not necessarily cost more.

The Principles of Resilience based design can be applied to a broad range of our built environment than just transport corridors discussed in the above case studies. Resilience based design of a system will focus on the following principles, for example for development of land, as illustrated in Figure 6:

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

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

c) Low impact on community functionality – low cost . . . accept damage (eg parks and play areas)

d) Systems are flexible and ductile (eg non-brittle materials for pipes, retaining walls 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.

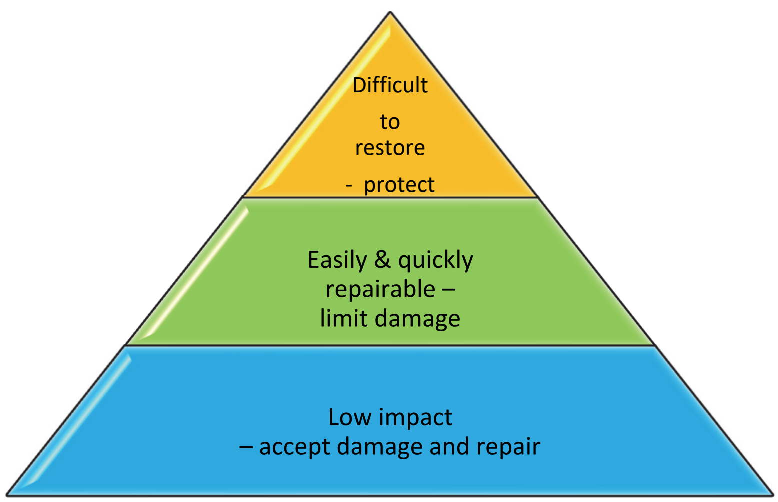

Figure 6. Principles for resilience-based design.

Guidance for Resilience-Based Design

Guidance on resilience-based design will help enhance our designs to achieve resilience. For example, recent guidance has been developed for design of cut slopes (Brabhaharan et al, 2018).

Conclusions

Recent earthquakes have highlighted the improvements made in life safety over the past 75 years or so but also indicate the vulnerability of our infrastructure and buildings that take a long time to recover their functionality. Our focus now needs to be on achieving continued functionality of society albeit at limited levels and quick recovery after earthquakes.

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 in a cost-effective manner.

There is a need to embed resilience-based design in our practice, and extend this to the design of buildings, which are essential for the society and economy to recover and function.

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