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Resilience based design for earthquakes

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ABSTRACT

Ensuring good earthquake performance while achieving economical design requires focus on resilience rather than purely on loss of life. Earthquake design practice in New Zealand has evolved during the past 90 years. Over the past 25 years, it has evolved from a purely factor of safety-based design to an emerging resilience-based design approach. This transformation has been variable, with resilience-based approaches being increasingly adopted in the transport sector, and design for life safety and recently low-damage design being adopted in the building sector.

Increasing awareness of the fragility of our infrastructure and the search for improved performance led to the development of the concept of resilience for transport infrastructure assets and networks, and a *resilience-based design* approach for cut slopes, rather than a factor of safety-based design or design for life safety alone. Resilience-based design is being adopted for lifeline infrastructure, where provision of service is critical.

Buildings are designed predominantly for life safety, and increasingly it is recognised that excessive damage has led to loss of functionality or demolition. This has led to a quest for low-damage design and also a focus on the performance of non-structural elements. A resilience-based design approach is also appropriate for buildings, as their quick return to functionality is also critical for societies to survive and function after earthquakes. This will provide a basis for an appropriately low damage design with timeframes for return to functionality based on importance for society.

This paper proposes that a resilience-based design approach be adopted across all sectors.

1 INTRODUCTION

Our learning from the consequences of past earthquakes, including significant loss of life, has led to the evolution of earthquake engineering over the years. Engineering for earthquakes in New Zealand has evolved over the past 80 to 90 years, particularly since the 1931 M7.8 Napier earthquake.

Early focus of earthquake engineering was on buildings and life safety, as there were many fatalities in earthquakes. As a result, a lot of our standards and codes focus on life safety. In countries such as New Zealand with 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 may not often be a direct consequence, but performance is important for response and recovery. The ability to respond and recover quickly may contribute to life safety, but also the social well-being of our communities, and economic recovery. This led to a focus on performance in the design of lifeline infrastructure. Given our increased understanding of the importance of resilience, there is a need to focus on design for resilience.

2 DESIGN FOR PERFORMANCE

There was early recognition among the geotechnical engineering practitioners of the need for performance-based design. The impetus initially came from the research into the earthquake performance of retaining walls during the 1970s and 1980s in New Zealand, which culminated in the publication of a summary of that research in the Road Research Unit Bulletin 84 (Wood and Elms, 1990). This report proposed methods of design for retaining walls, classified as flexible, stiff or rigid, and included assessment of the displacement of retaining walls based on Newmark's sliding block model. In Europe, Ambraseys and Menu (1995) published statistical analyses of the earthquake displacement of slopes based on a collection of past earthquake records and the Newmark sliding block approach. Together, these provided a means of assessing earthquake displacement with some level of statistical confidence. During the 1990s in New Zealand, there was also an increased use of reinforced soil and soil nailed walls, which were well suited to design allowing displacement. These developments, together with the increased focus on lifelines, provided the opportunity for geotechnical designers to design retaining walls to desired levels of maximum displacement performance 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. Appreciating 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, with 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 (NZ Bridge Manual)	No more than 150 mm wall displacement, with minor damage with cracking of road.	670 years	0.35g
Contingency Level (M7.5 Wellington Fault)	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 and other 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 incorporating anchor bars with post-yield ductile behaviour.

This performance-based design approach was also adopted 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 the Terrace Tunnel approach walls (O'Reily and Brabhaharan, 2006), see Figure 1.

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

3 CONCEPT OF RESILIENCE

Research into strategies for the management of the risks to transportation networks from natural hazards in the period 2001-2006 led to the development of the concept of resilience for road networks, together with metrics to measure resilience (Brabhaharan, 2004).

Resilience can be defined as *the ability to recover quickly to restore the level of service after an event*, from the perspective of transportation networks (as well as other lifeline infrastructure). This is illustrated conceptually in Figure 2. This can be characterised by the metrics of *availability state* (representing the reduced level of service) and *outage state* (representing the time required to restore service) for transportation infrastructure, and a similar framework has since been used for other lifeline infrastructure.

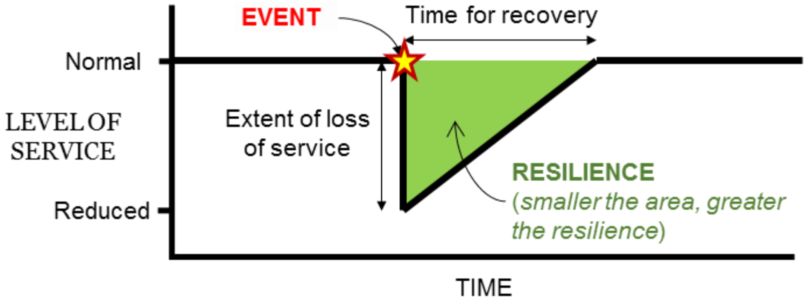

Figure 2. Concept of Resilience for lifeline infrastructure

Exploration of measures to enhance resilience based on network-wide resilience studies highlighting the vulnerabilities of transportation networks to natural hazards have led to a realisation that the resilience expectations can be significantly different depending on the resilience context. Similarly, new infrastructure will have different resilience expectations depending on the network context. For example, infrastructure on a transportation corridor with very little redundancy, will require a greater level of resilience (for example in Wellington) than similar infrastructure where there is plenty of redundancy (for example in Christchurch).

4 DESIGNING FOR RESILIENCE OF TRANSPORTATION INFRASTRUCTURE

4.1 Transmission Gully expressway case study

There is a critical need for resilience in the transport network in Wellington, given the poor resilience of the existing routes due to the rugged terrain, large cut and fill slopes, high seismicity and lack of redundancy. This need led to an early focus on resilience during the development of an alternate Transmission Gully route north of Wellington. A case study of its conceptual design showed that an early focus on resilience can help achieve greater resilience of lifeline infrastructure at no additional cost (Brabhaharan, 2009). This resilience focus during conceptual design involved modifying the route alignment and road form to cross a major active earthquake fault on soil embankments rather than the viaducts previously proposed. Though both embankments and viaducts would be damaged by rupture of the fault, an embankment can be quickly restored by earthmoving machinery, reducing the outage time to within a few days, compared to a viaduct, which would take many months to years to restore. The faster recover possible with an embankment form 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 to achieve, unless there was a focus on *design for resilience* from early stages of projects.

4.2 Observations from Kaikōura earthquake

Observations of failures in the 2016 Kaikoura earthquake along State Highway 1S between Picton and Christchurch showed that:

- road access was restored quickly in places where there were small to moderate size failures, with limited repair and disruption costs; but
- it took over a year to restore limited access where there were larger landslides, see Figure 3. The restoration of limited access by clearing and stabilizing large landslides involved very large costs and the disruption of a nationally significant transport corridor led to major disruption costs to the economy.

Figure 3. State highway and rail closed by large landslides in the 2016 Kaikoura earthquake, New Zealand.

This highlights the need for considering resilience of transportation networks, as well as other infrastructure, so that more resilient infrastructure can be developed over time.

4.3 Research into earthquake design and performance of cut slopes

Transportation projects to form or improve roads through rugged terrain are a challenge from a resilience perspective. The active tectonic environment, steep rugged slopes and tectonically deformed and fractured rocks mean that steep cut slopes formed along transport corridors can perform poorly in hazard events such as earthquakes. Therefore, flatter slopes and extensive stabilisation measures are required, with associated large costs. There was very little research or guidance for the seismic design of cut slopes in New Zealand, or globally. To address this issue, research into the seismic design and performance of high cut slopes was carried out by Opus during 2014-2016 with funding from the NZ Transport agency. This led guidance for the seismic design of cut slopes (Brabhaharan et al, 2018), which proposes a resilience-based design approach, as discussed below.

4.4 Resilience-based design

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.

The focus is often 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 (as illustrated from the Kaikōura earthquake example); and
- avoiding large failures that are likely to close the highway and take a long time to restore access.

This principle of resilience considering loss of access and the outage period has intuitively 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 prioritised for strengthening to enhance resilience.

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. These have therefore not been prioritised for strengthening.

The resilience-based design approach for infrastructure can be illustrated conceptually using the diagram in Figure 4.

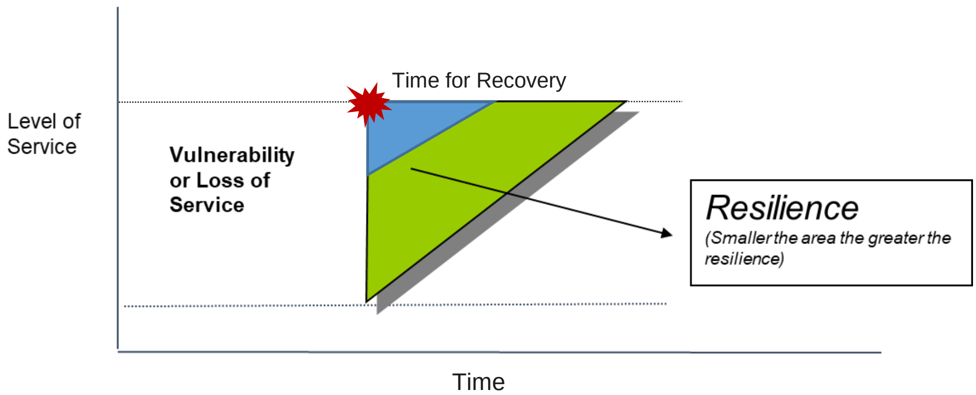

Figure 4. Enhancing Resilience through reduced reduction in functionality and time for recovery

A resilience-based design approach could help enhance resilience by limiting the reduction in service or functionality in an event, and also adopting a design that enables functionality to be restored quickly (blue triangle compared to the green triangle). This approach would help achieve a desired post-earthquake return to functionality at an optimum cost.

Another important aspect of resilience-based design is understanding the resilience needs of each transportation link or other piece of infrastructure. This will depend on the criticality of the route, based on the importance of the route and its vulnerability. The criticality of the route will depend on communities served, importance for lifeline utility restoration access, critical facilities dependent on the route, availability of alternative routes etc. For example, a section of the route may have very little or no redundancy (eg Transmission Gully expressway example above), while another route may have abundant redundancy of access such as in Christchurch city.

While the resilience-based design guidance has been developed for road cuttings, it can also be used for the wider transportation networks and other infrastructure.

The New Zealand Bridge Manual requirements go part way towards a resilience-based design approach for the design of bridges, where it specifies certain performance requirements for different earthquake events, and some characterisation of the relative importance of state highway routes.

5 RESILIENCE-BASED DESIGN OF THE BUILT ENVIRONMENT

5.1 Key features of the Approach

The resilience-based design approach developed for transportation networks, and especially cuttings, have a wider application to infrastructure networks, that all provide service to users and the community at large.

Strategic features of a resilience-based design approach would be:

1) Understanding the resilience needs or expectations of different infrastructure and their components, depending on criticality and vulnerability. This included understanding of any inter-dependence of infrastructure networks.
2) Design that provides the necessary level of functionality and time for recovery, depending on the identified criticality and resilience expectations.
3) Focus on the principles of resilience-based design as outlined below.

5.2 Principles of resilience-based design

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 5:

1) Difficult – costly – time consuming to repair components . . . minimize damage (eg. bridges providing access, trunk utilities)
2) Easily - quickly repairable parts . . . accept limited repairable damage (eg roads, distributor pipes)
3) Low impact on community functionality – low cost . . . accept damage (eg parks and play areas)
4) Systems are flexible and ductile (eg non-brittle materials for pipes, retaining walls that can displace)
5) 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.

Resilience-based design following the strategic features and associated principles would help achieve a built environment that would provide a desired level of resilience.

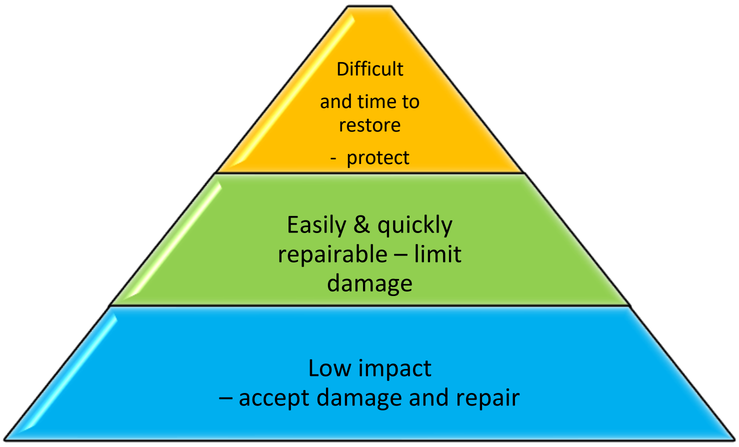

Figure 5. Principles for resilience-based design

The resilience-based design approach can be directly applied to a range of infrastructure in our built environment, as they all provide a level of service that is relied upon by the community.

5.3 Application to buildings

The resilience-based design approaches developed in the infrastructure sector also has application in the building sector. Buildings have traditionally been designed for life safety, but there is increasing focus on low-damage design and performance of non-structural components. These developments both focus on achieving better performance of buildings in earthquakes. Comerio and Holmes have highlighted the importance of considering performance and downtime in considering the strengthening of buildings.

The resilience philosophy can be adapted to cater for buildings – both residential and commercial. For infrastructure, the focus has been on the level of service provided by the infrastructure and the time taken for recovery. The current focus on life safety and low damage for buildings needs to be extended to consider the consequences of damage to occupation and functionality, which are both important to society. This needs to be considered together with time for return to occupation and functionality. This would not only bring the low-damage and non-structural element performance initiatives within a functionality and time context, but also focus the holistic performance of buildings within a resilience framework, which would help align this with societal impacts and needs.

The resilience concept could then be re-framed for buildings as illustrated in Figure 6.

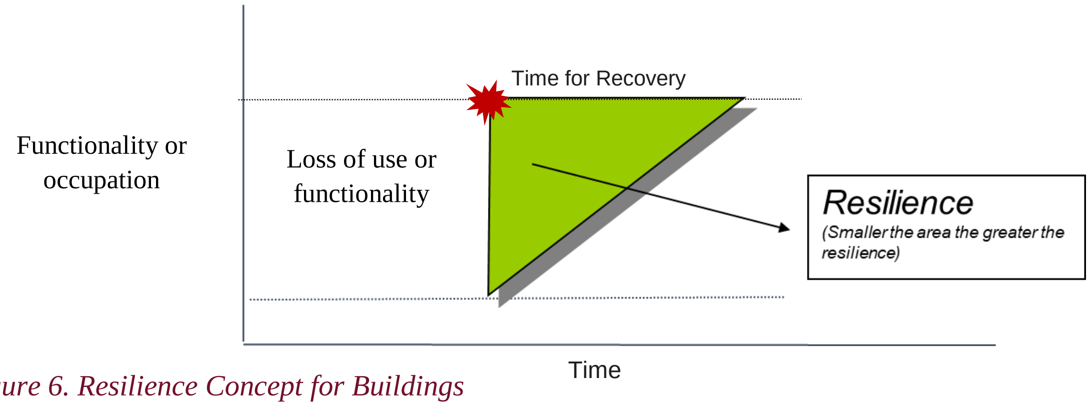

Figure 6. Resilience Concept for Buildings

A resilience-based design concept for buildings will enable the engineering professionals to design the building structure, non-structural elements, services etc, all to be consistent and focussed towards providing functionality and occupation in a holistic manner, to meet the needs of society.

6 CONCLUSIONS

Recent earthquakes have highlighted the improvements made in life safety over the past 75 years, 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, that is, enhanced resilience.

Over the past 25 years, 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*. *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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