Recent Advances in Improving the Resilience of Road Networks

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ABSTRACT: The Hawke’s Bay Earthquake struck in 1931, and not only did it cause devastation to the buildings in Napier, but also to the transport infrastructure. Roads were made impassable by liquefaction induced lateral spreading of embankments and also landslides.

Some recent research and studies have focussed on road networks, and how their resilience can be improved through spatial road risk assessment methods, economic analyses of risk mitigation and implementation issues in the New Zealand context. Research just concluded considers the resilience of road networks and a framework for improving the resilience by considering key parameters that are important to the community.

The resilience is represented by damage and availability of the network combined with the outage (time network is impaired). The key influences that impact on the target (desired or tolerable) level of resilience of roads are life safety, disruption, loss of access for emergency services, need for lifeline restoration, and wider economic impacts.

Target resilience levels can be set for different links in the road network, and the resilience gap can be assessed as the difference between the likely resilience in hazard events and the desired or target resilience. This will facilitate development of mitigation measures to enhance the resilience, and these can then be incorporated into the strategic asset management for the road network.

Figure 1  Road and Railway damaged in 1931 Hawke’s Bay Earthquake
1 INTRODUCTION

Transportation networks are key lifelines for communities and are vital for response and recovery after major hazard events such as earthquakes. It is important that our transport networks are resilient and vital links would be able to maintain functionality in the event of major earthquakes and other hazard events.

The Hawke’s Bay earthquake of 1931 not only caused heavy damage to the buildings, it also cut off key transport links in the region, see Figure 1. This included damage to bridges, roads, railway lines, port facilities and the airport. Other recent hazard events, such as the Manawatu storm of February 2004 showed that key transport links remain vulnerable to natural hazards such as earthquakes.

Often the improvement to the resilience of transport networks is seen as difficult to achieve, given the extensive networks and the terrain. This has led to a reactive approach to deal with such risks. There is a need for a systematic approach to enable the assessment, prioritisation and management of the risks to road networks.

Some recent advances have addressed some of these issues, and some systematic approaches have been developed to manage the risk to road networks to achieve resilient road networks. This paper presents some of the recent advances in improving the resilience of transport networks.

2 TRANSPORT NETWORK PERFORMANCE IN THE HAWKE’S BAY EARTHQUAKE

2.1 The Hawke’s Bay Earthquake of 1931

The shallow Hawke’s Bay Earthquake of 3 February 1931, with a magnitude of $M_w$ 7.8 is the second largest New Zealand earthquake in recorded New Zealand history, and caused the most damage to the built environment and caused the most casualties of any New Zealand earthquake. It was felt over most of the country, from Auckland in the north to Invercargill in the south. The intensities reached Modified Mercalli X (MM10) in the central area.

The earthquake caused severe and widespread damage to the buildings in the region, and this is well documented. The damage to lifelines in the 1931 earthquake is covered by Evans (2006).

2.2 Damage to Transport Infrastructure

The 1931 earthquake caused widespread damage to roads and railways. Damage to some of the main railway lines is shown in Figure 1, and indicates that liquefaction induced lateral spreading may have led to this damage. The roads also experienced severe damage due to both liquefaction induced lateral spreading of road embankments, see Figure 2, and also due to the collapse of bridges, see Figure 3, and landslides, see Figure 4.

Figure 2 Damage to Road in 1931 Napier Earthquake  Figure 3 Bridge Collapse in 1931 Napier Earthquake
The earthquake also caused extensive damage to the port facilities, see Figure 5.

![Landslide in 1931 Napier Earthquake](image1.png) ![Napier Port Wrecked by 1931 Earthquake](image2.png)

Figure 4 Landslide in 1931 Napier Earthquake

Figure 5 Napier Port Wrecked by 1931 Earthquake

### 2.3 Lessons from 1931 Earthquake

The 1931 earthquake caused extensive damage to the transport network including roads. Failure of key parts of the network had a major impact on response and recovery. For example, damage to the Redcyffe bridge at Waiohiki near Taradale meant that a spare transformer could not be brought to the substation, which had a major impact on the restoration of power supplies (Evans, 2006).

This highlights the importance of considering the transport networks carefully, and prioritising the links in the network, as to their performance expectations in a major event. This would enable the resilience of the key higher priority links to be improved to achieve a required level of performance.

### 3 DEVELOPMENTS SINCE NAPIER 1931

There have been significant improvements in the design of bridges since the 1931 Napier earthquake. National Roads Board and its successor Transit New Zealand have developed a *Bridge Manual* which specifies its design requirements, including earthquake design requirements. With the improvement in design requirements, the design and construction of bridges has improved over the first sixty years since 1931.

In the 1990s, Transit New Zealand has made a concerted effort to screen its bridge stock for earthquake performance. A screening methodology was developed by Opus International Consultants (1998), and this was widely applied to the state highway bridge stock, which enabled Transit to prioritise bridges that require further detailed assessment and retrofit. This process of detailed assessments and retrofit is currently underway. In addition, Transit undertook detailed assessments and retrofit of key bridge structures such as Wellington’s Thorndon Overbridge, see Figure 6, and the Auckland Harbour Bridge.

![Thorndon Overbridge in Wellington Retrofitted for Earthquake Performance](image3.png)

Figure 6 Thorndon Overbridge in Wellington Retrofitted for Earthquake Performance
Lifelines studies during the past 15 years have broadly identified the vulnerabilities of road networks in a number of cities and regions to earthquakes and other natural hazards. This has spurred retrofit of some key local authority bridge structures in some cities, eg Aotea Quay ramps in Wellington and the Melling Bridge in Lower Hutt.

However, there has been little consideration of the resilience of the overall road networks, and their performance requirements, until recently.

4 ROAD NETWORK RISK MANAGEMENT

Research by Opus International Consultants, supported by Transfund New Zealand, and application to real road networks, under contract to some road controlling authorities, has led to the development of a systematic risk assessment and management approach using geographical information systems (GIS). The spatial approach uses a geographical information system (GIS) to facilitate the capture, assessment and presentation of the risk information, and enabled the characterisation, risk assessment, prioritisation and consideration of risk mitigation for whole road networks (Brabhaharan, 2002).

A spatial approach to risk assessment was undertaken for the Wellington City road network, and enabled the prioritisation, risk assessment, consideration of mitigation and economic analyses under a GIS framework, see Figure 7. This led to implementation of risk mitigation to improve the resilience of prioritised sections of the road network, starting from Ngaio Gorge Road (Brabhaharan and Saul, 2005).

![Figure 7 Prioritisation of Risk Mitigation based on Benefit/Cost Ratio from Economic Analysis](image)

5 WHAT LEVEL OF RESILIENCE?

One of the key questions in risk management is what level of resilience needs to be achieved. This is fundamental to achieving a level of performance that would enable the response and recovery after events, and ensure that the community can function normally as quickly as possible after major hazard events such as earthquakes.
This requires us to define resilience for a road link in a network. Prof Ian Buckle proposed defining Resilience as a function of vulnerability and rate of recovery at the 2005 Joint US – New Zealand Critical Infrastructure Workshop.

\[
\text{Resilience} = f (\text{vulnerability, rate of recovery})
\]

This was conceptualised in the diagram in Figure 8.

![Figure 8 Conceptual Definition of Resilience](image)

Resilience of a road link can be defined as the combination of its low vulnerability to degradation in a hazard event and the short time within which it can be reinstated after hazard events. Conversely, loss of quality of access (service) and outage (period of loss of quality of access) are critical to define the performance of road networks.

This can be related to the Performance States (or Resilience States) proposed for road links by Brabhaaran et al (2006), and applied to the Western Bay of Plenty Road network (Speed and Brabhaaran, 2006). Performance states developed for considering the likely performance of road links in Western Bay of Plenty and comparing them with the expected performance of road links are presented in Tables 1 to 3, and include:

(a) Damage State - Represents the severity of damage to the road and represents the extent and cost of damage repairs, and the damage states adopted are presented in Table 1.

(b) Availability State - State indicates whether the road section would be able to be used either at full level, at various reduced levels or not at all. This gives an indication of the extent of access within the road network after an event, and the degree of access is presented in Table 2.

(c) Outage State - Indicates the duration over which the road will be in the Availability State i.e. the duration of loss or reduced access in links along the road network, and is defined in Table 3.

(d) Disruption State - Disruption State is a combination of the Availability and the Outage giving an overall indication of the level of disruption caused by the event at each road section.

An example of the availability state developed for the Western Bay of Plenty road network in a 500 year return period earthquake event is presented in Figure 9. This shows what the post-event availability for use would be for various links of road in a road network.

The performance expectations of roads (or desired level of performance) can be determined by considering the uses of the road link:

- Safety of road users and others
- For emergency services access
- Restoration of other lifelines dependent on access
- Alternative access in the event of closure of other routes
- Access for recovery after events
- Restoration of mobility for return to socio-economic mobility.
Table 1  Damage State

<table>
<thead>
<tr>
<th>Damage Level</th>
<th>Damage State</th>
<th>Damage Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Slight</td>
<td>Only slight damage that requires routine maintenance</td>
</tr>
<tr>
<td>2</td>
<td>Light</td>
<td>Minor damage requiring clean up of small slips (few cubic metres) and debris and culverts</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>Moderate damage requiring removal of moderate volume of slip debris (tens of cubic metres), small scale repair of underslips (less than 2 m high walls) and minor repair to walls, culverts and other structures</td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
<td>Severe damage requiring clearing of large volumes of slip materials (hundreds of cubic metres) and stabilisation, significant structures to repair underslips and major repair to walls, replacement of culverts and other structures</td>
</tr>
<tr>
<td>5</td>
<td>Extensive</td>
<td>Extensive damage requiring clearing of major volumes of landslides and stabilisation, large structures to repair underslips, damages to walls and other structures</td>
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Table 2  Availability State

<table>
<thead>
<tr>
<th>Availability</th>
<th>Availability Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Full access except condition may require care.</td>
</tr>
<tr>
<td>2</td>
<td>Available for slow access, but with difficulty by normal vehicles due to partial lane blockage and deformation.</td>
</tr>
<tr>
<td>3</td>
<td>Single lane access only with difficulty due to poor condition of remaining road.</td>
</tr>
<tr>
<td>4</td>
<td>Road accessible single lane by only 4x4 off road vehicles.</td>
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<tr>
<td>5</td>
<td>Road closed and unavailable for use.</td>
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Table 3  Outage State

<table>
<thead>
<tr>
<th>Outage Level</th>
<th>Outage State</th>
<th>Damage Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Open</td>
<td>No closure, except for maintenance</td>
</tr>
<tr>
<td>2</td>
<td>Minor</td>
<td>Condition persists for up to 12 hours</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>Condition persists for 12 hrs to 3 days</td>
</tr>
<tr>
<td>4</td>
<td>Severe</td>
<td>Condition persists for 3 days to 21 days</td>
</tr>
<tr>
<td>5</td>
<td>Long term</td>
<td>Condition persists for &gt; 3 weeks</td>
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</table>

The performance expectations of the road network could also be mapped in GIS based on the importance and usage of the different road links forming the network.
PERFORMANCE GAP

The Resilience Gap can be assessed as the Performance Gap for the road links in the network. Using the performance states defined in Tables 1 to 3, this could be assessed as the difference in the outage (between the likely outage after an event, and the tolerable outage for return to functionality) for given levels of availability.

For example, for no availability (closure of road), the performance gap can be calculated as the likely closure period after say a 500 year return period earthquake event and the tolerable outage to ensure that the roads provide access for response and recovery. Having mapped the performance states in GIS, the tolerable outage for various road links and various levels of availability can be mapped, and the performance gap for various availability states can be derived spatially for the road network, and presented visually. This would provide the basis for consideration and prioritisation of risk mitigation actions to reduce this gap or shortfall in performance.
7 ENHANCEMENT OF RESILIENCE

The enhancement of resilience of a road network would require consideration of variety of actions:

- Reduction in vulnerability to enhance performance in events
- Readiness planning to reduce the time taken for the road link to be restored
- Planning of alternative access or road links.

It is importance that initiatives to reduce the risk or enhance the resilience are carried out in an integrated manner. Brabhaharan and Moynihan (2002) proposed a five level consideration of initiatives to enhance the resilience, and these are presented in Table 4.

<table>
<thead>
<tr>
<th>Table 4 Levels of Implementation</th>
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<tbody>
<tr>
<td><strong>Level</strong></td>
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<td>-----------</td>
</tr>
<tr>
<td>Level 1</td>
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<tr>
<td></td>
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<td>Level 2</td>
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<tr>
<td>Level 3</td>
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<tr>
<td>Level 4</td>
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<tr>
<td>Level 5</td>
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It is important to ensure that there is co-ordination between Transit NZ and regional and territorial local authorities, to ensure that the road networks are considered in an integrated manner. In addition, co-ordination with other lifeline utilities is also important. Improvements in funding frameworks will also facilitate proactive action by road controlling authorities in achieving more resilient road transport infrastructure.

The management of the risk to the road network should not be considered in isolation, but together with other issues related to asset management for the network, such as safety, congestion, traffic growth and maintenance. This will enable the development of an integrated strategic asset management framework, and build risk mitigation within the overall asset management plan.

8 CONCLUSIONS

The Napier 1931 Earthquake highlighted deficiencies in our transport infrastructure and illustrated the importance of transportation networks for rapid response and recovery. While significant improvements have been made in the design and construction of bridges and roads, there has been little consideration of the transport networks as a whole, and their performance requirements.

Recently a number of systematic approaches have been developed to assess the risk to road networks with the aid of spatial Geographical Information System tools, and consider and prioritise mitigation measures to enhance the resilience through consideration of economic analysis and performance levels. It is also important that these measures be considered in an integrated manner across road controlling authorities and other lifeline utilities.

While these developments have been generally developed for road networks, the approaches are equally applicable to other transport networks, particularly railways, and also other lifeline utilities.
ACKNOWLEDGEMENTS

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The Hawke’s Bay earthquake photographs are courtesy of the Alexander Turnbull Library.

REFERENCES:


