Reducing Infrastructure Outages Through Integrated Infrastructure Resilience Investment Programme

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Abstract

Infrastructure networks (e.g. transport, water, electricity) support life and the economy of communities of all sizes around the world. Findings from major natural hazard events have shown that damage to one or more infrastructure networks can result in serious social and economic consequences. One example of such a significant event in recent times is the 2016 Mw 7.8 Kaikōura earthquake that occurred in New Zealand. The earthquake caused widespread damage to the exposed built environment, severely damaging large sections of a State Highway and of key railway lines, resulting in direct and indirect impacts due to disrupted services. Events such as this, and the 2010-2011 Canterbury Earthquake Sequence have demonstrated the critical need for New Zealand to take measures to prepare for, respond to, and recover quickly from future major events.

The subject matter of this paper is the Wellington Lifeline Group's Regional Resilience Project, a project aimed at improving the resilience of lifeline utility services to Wellington (the capital of New Zealand) and its surrounding cities. A key input to the modelling carried out in the project was service outage maps developed by GNS Science for infrastructure networks chosen for the project. The focus of this paper will be on the transportation networks (e.g. roads and rail), discussing the potential severity and extent of physical damage expected, and the likely time required to fix the damage and recover the services following a major earthquake in the region. The paper will also demonstrate the benefit of implementing proposed transportation infrastructure resilience projects in reducing modelled outage times.

Keywords: resilience, infrastructure, earthquake, recovery, service outage, damage, road, rail

1. Introduction

New Zealand is a unique place on the Earth’s surface and is positioned along the collision zone of two of the Earth’s major tectonic plates, the Pacific plate and the Australian plate (Fig. 1). The forces which have created the countrys’ dramatic and beautiful landscapes also make it extremely prone to natural hazards such as earthquakes, volcanoes, floods etc. Thousands of earthquakes occur every year that can be too small to be felt, but occasionally the country experiences some large earthquakes (Fig. 1). One recent example of a major event in the country is the 2016 Mw 7.8 Kaikōura earthquake [1]. The earthquake caused widespread damage to the exposed built environment, particularly severely damaging large sections of a State Highway and key railway lines, resulting in serious direct and indirect impacts due to disrupted services [2]. Events such as this, and the 2010-2011 Canterbury Earthquake Sequence ([3], [4]), have imparted the critical need to take measures to prepare for, respond to, and recover quickly from future major natural disasters in the country.

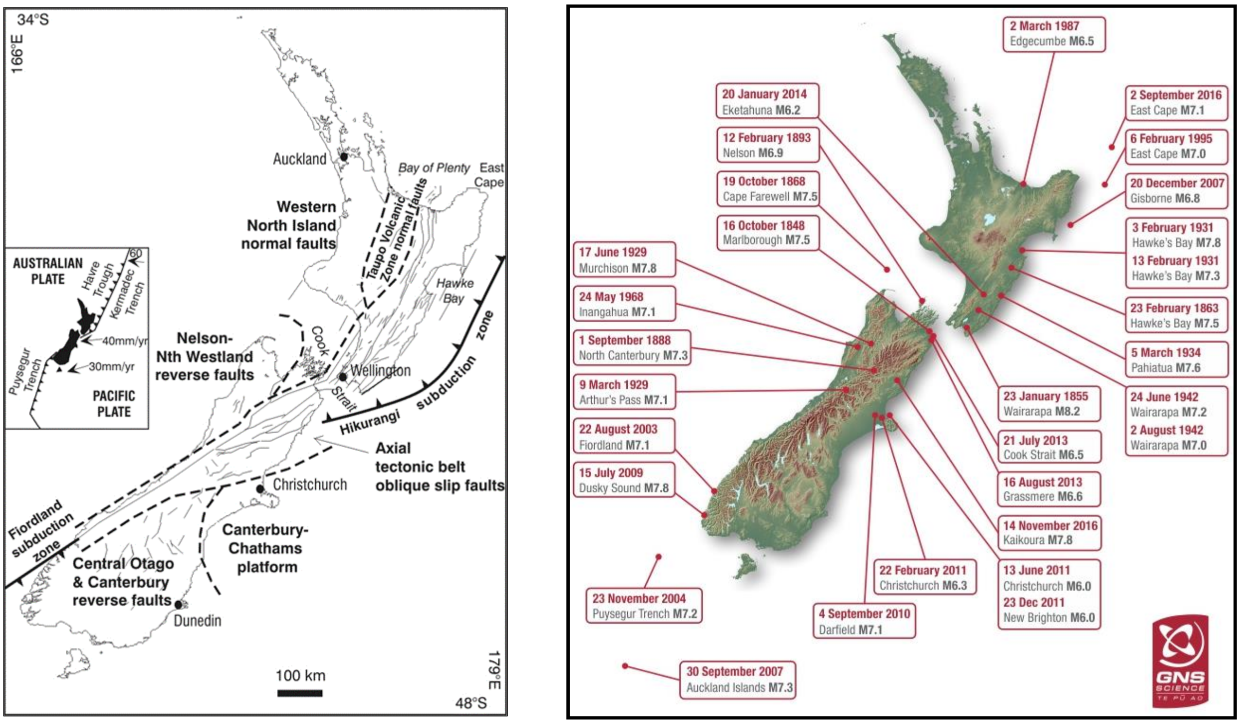


Fig. 1 – Tectonic setting of New Zealand (*left*); shallow (≤ 30km depth) large earthquakes since 1848 (*right*).

The subject matter of this paper is the Wellington Lifeline Group’s Programme Business Case (WeLG PBC, [6]), a project aimed at improving the resilience of lifeline utility services to Wellington (the capital of New Zealand) and its surrounding cities. The project, through a combination of qualitative and quantitative assessment process (Fig. 2), demonstrated how economic disruption (both at regional and national level) of a major natural disaster in the region could be restricted by implementing an accelerated and phased programme of infrastructure resilience investments. As part of this project, physical damage and service outage modelling on ten different lifelines/utilities (e.g. water, electricity, fuel etc.) were conducted by GNS Science; the focus of this paper though will be on two key transportation networks (road and rail) in the study area (Fig. 3). Details of the modelling work carried on other infrastructures can be found elsewhere (e.g. [7]).

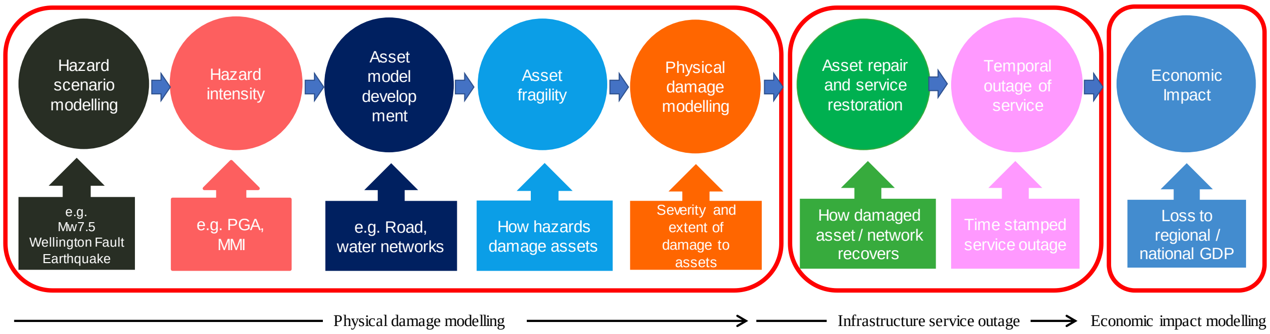
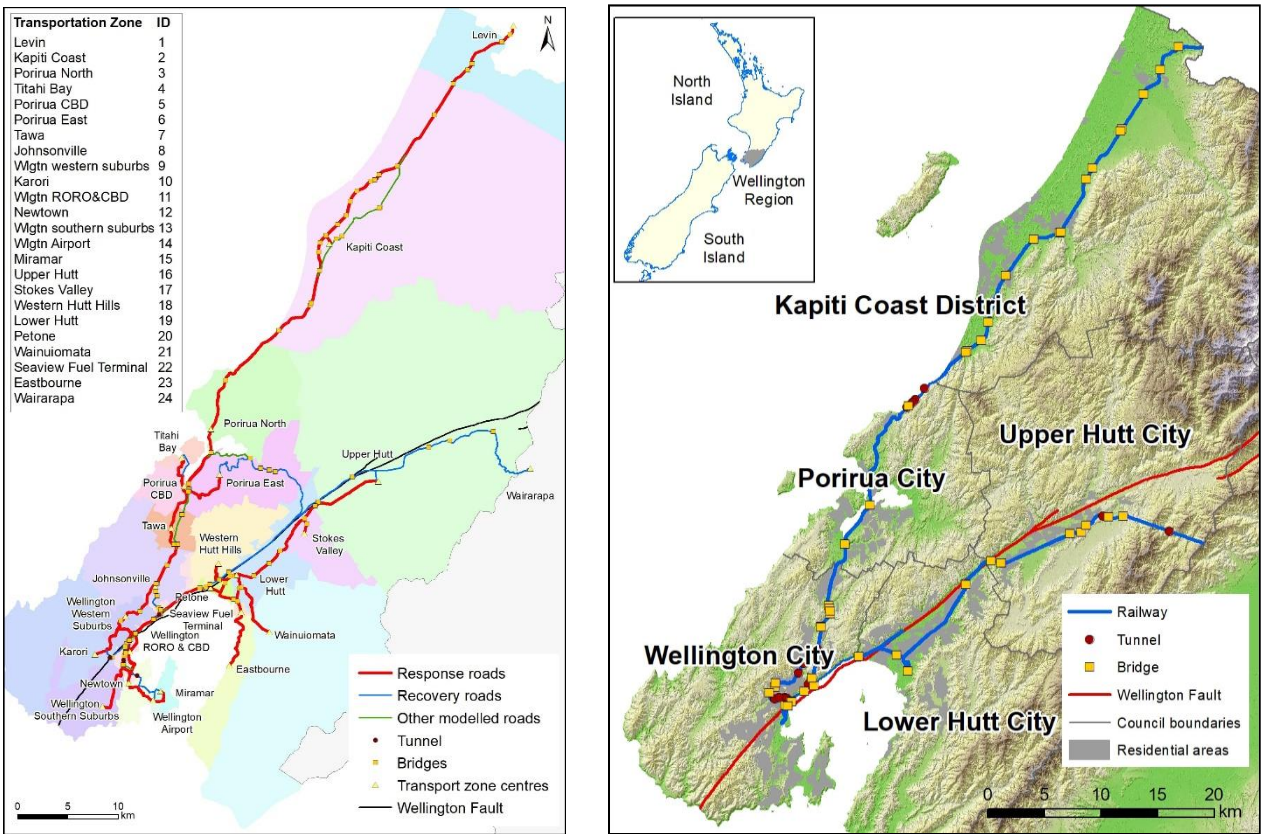


Fig. 2 – Impact modelling workflow



Transportation Zone	ID
Levin	1
Kapiti Coast	2
Porirua North	3
Titahi Bay	4
Porirua CBD	5
Porirua East	6
Tawa	7
Johnsonville	8
Wlgtn western suburbs	9
Karori	10
Wlgtn RORO&CBD	11
Newtown	12
Wlgtn southern suburbs	13
Wlgtn Airport	14
Miramar	15
Upper Hutt	16
Stokes Valley	17
Western Hutt Hills	18
Lower Hutt	19
Petone	20
Wainuiomata	21
Seaview Fuel Terminal	22
Eastbourne	23
Wairarapa	24

Fig. 3 – Modelled road (*left*) and rail (*right*) networks in the study area

2. Hazard Scenario

A M_w7.5 Wellington Fault earthquake scenario was chosen for impact modelling in this project for many reasons: (a) it is well-researched and commonly used for insurance risk assessments (e.g. [8]), business continuity planning etc; (b) it has a probability of occurrence of 10% in the next 100 years (and therefore a credible event) and is also a principal contributor to the 1 in 500-year earthquake hazard which is used to define the seismic loading levels for the NZ building code for general multi-story commercial and residential buildings; (c) a recovery of the region can be modelled following this major event; (d) it has many similar characteristics to other potential large earthquakes in the region (e.g. earthquakes on Ohariu Fault to the west of Wellington) so any intervention measure to mitigate the impacts from a Wellington Fault earthquake will also be effective against similar large earthquakes from other sources in the region; and (e) by investing in improving infrastructure resilience to restrict the impact from a maximum credible scenario such as the Wellington Fault earthquake, the benefits from proposed interventions will also minimise the impact from higher frequency but lower impact earthquakes in the region (and potentially also from other hazards such as flooding etc., dependant on the investment programme), or larger events that may occur at larger distances from Wellington (e.g. an Alpine Fault earthquake, which would more seriously impact the NZ South Island).

For damage modelling the following hazards related to the Wellington Fault earthquake were considered: (a) ground shaking; (b) fault rupture; (c) co-seismic subsidence caused by fault movement; (d) landslides; and (e) liquefaction and lateral spreading. Estimated peak ground accelerations at central business district area of the five cities are (Fig. 4): ≈ 0.76g (Wellington), ≈ 0.72g (Lower Hutt and Upper Hutt), ≈ 0.44g (Porirua), ≈ 0.28g (Kapiti). More details on the hazard models used can be found in Sadashiva et. al. [7].

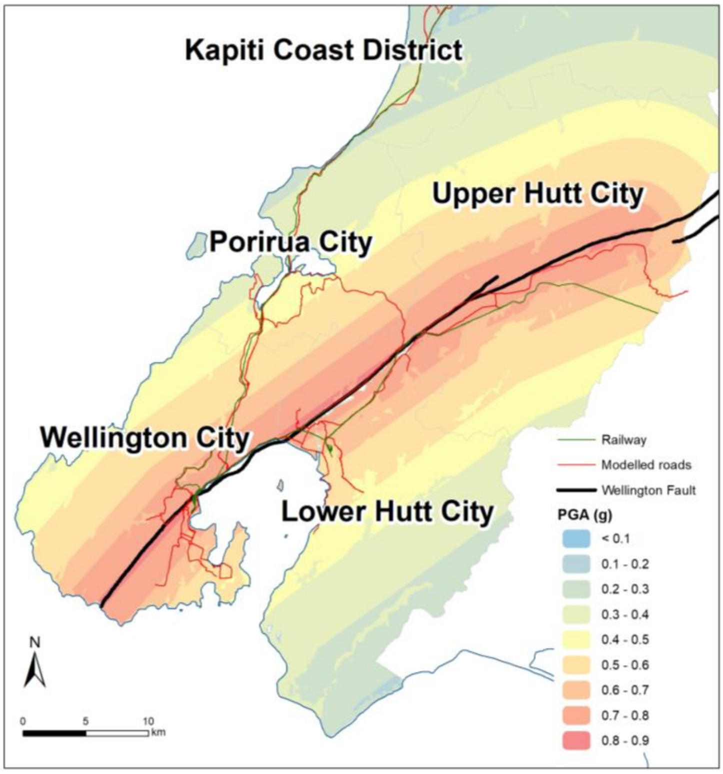


Fig. 4 – Modelled peak ground accelerations from the Wellington Fault earthquake scenario

3. Asset Model

The road network within the study area was simplified into 24 transportation zones (Fig. 3) and the routes chosen for modelling were based on pre-existing road hierarchies and included all national, high volume and regional roads in the study area, as well as some arterial and collector roads.

The geospatial data relating to the routes were sourced from the Waka Kotahi - New Zealand Transport Agency (a crown entity responsible for building, maintaining and operating the State Network in NZ) and from the five local councils participating in the project. For the rail network, the geospatial representation of the rail routes in the study area (see Fig. 3) was provided by KiwiRail (a state-owned enterprise and the largest rail transport operator in NZ).

Past and recent earthquakes (see Fig. 5 for example) have shown that bridges, tunnels and retaining walls are generally vulnerable to ground shaking while significant damage to the road and/or rail track are also caused due to ground failure (e.g. liquefaction, surface fault rupture). Therefore, all the above assets along the routes were included for damage modelling.

The geographic locations of the various structures along the road and rail routes, and the corresponding asset data / attributes defining the structures (e.g. type, age, construction material, structural configuration etc.), were stored in GIS layers. The continuous line segments representing the routes were then discretized into segments (typically start / end points of access or egress) and spatially overlaid on the hazard maps to enable each exposed segment to be related to the potential geological hazard features (e.g. liquefaction susceptibility) at its location.

On left: damage to road and large offset of a rail track due to landslide. *On right*: rail bridge span dislocated from an abutment due to fault rupture

On left: severely distorted and misaligned rail tracks due to fault movement. *On right*: a cracked tunnel wall

Fig. 5 – Examples of damages to road and rail networks in the 2016 M_w 7.8 Kaikōura earthquake

4. Damage and Service Outage Modelling

Potential physical damage to the two networks when exposed to the Wellington Fault earthquake scenario was modelled following the workflow shown in Fig. 2. Two assessment cases were undertaken to demonstrate the effectiveness of proposed infrastructure investments. These are discussed below.

4.1 Base Case

In this case the earthquake is assumed to strike the assets in their current "as-is" state. To model the potential physical damage to the assets, a fragility model [9] was selected based on the asset data provided and assigned to each exposed asset. Where there were any gaps in the data provided, additional information / proxy attributes on the assets were provided (where available) by the roading teams. A degree of engineering judgement was also required to be applied when there was no/insufficient asset data for modelling purposes.

Damage to one or more assets can result in disruption to the normal traffic flow (i.e. pre-earthquake condition) at any road segment. The damage state for each asset resulting from the modelling was translated to Service Disruption Levels (SDL) [10] of traffic flow from their unimpeded capacity. These range from SDL0 (no disruption) to SDL4 (complete closure) with the intermediate levels representing either partial closure or imposition of various levels of restriction – e.g. speed restrictions, single lane flow or possible limits on vehicle weights etc.

Fig. 6 shows the base-case road service disruption map for the earthquake scenario considered for this project. The map shows the critical SDL for each road segment. That is, for example consider a road segment with a bridge and a tunnel; if the SDL due to bridge damage = 3, SDL due to tunnel damage is 2, and the SDL from damage to road itself is 4, then the final SDL reported for the road segment is the maximum SDL (= 4 in this example). For the rail network, a base-case damage state map was generated (Fig. 7). Here, similar to the road disruption map, the critical damage state (from all exposed assets) for each track segment is shown on this map.

The output from damage modelling was reviewed by the respective roading teams and KiwiRail during consultation on service restoration times. Where it was required to assist in estimating the times for providing access between the transportation zones, results from an earlier study [11] were also discussed and applied by the roading managers. Repair strategies/sequences were explored considering network operation hierarchy, inter and intra dependencies of the network components, priority/critical customer needs, availability of repair equipment/machines, replacement materials etc. Two levels of service were considered for roads: (a) response (i.e. access for vehicles such as a 7.5T two-axle van used for emergency purposes during initial days following the earthquake); and (b) recovery (i.e. access for all vehicles). Similarly, rail services were staged into two service levels – freight and passenger services.

The estimated likely base-case restoration times for road access between the transportation zones for the two levels of services is shown in Table 1. For the base-case rail network, a gradual recovery of the freight services is expected to start from a year after the earthquake, plus another two years for its full recovery. It is estimated to take 3.5 years following the event to restore full passenger rail service to pre-earthquake levels of service.

A key feature of the PBC was to understand interdependencies between lifelines and incorporate them in the modelling. For example, road access (and electricity/fuel) is required to undertake repairs on damaged water networks [7]. Therefore, the road restoration times estimated were a key input when calculating water service outage times.

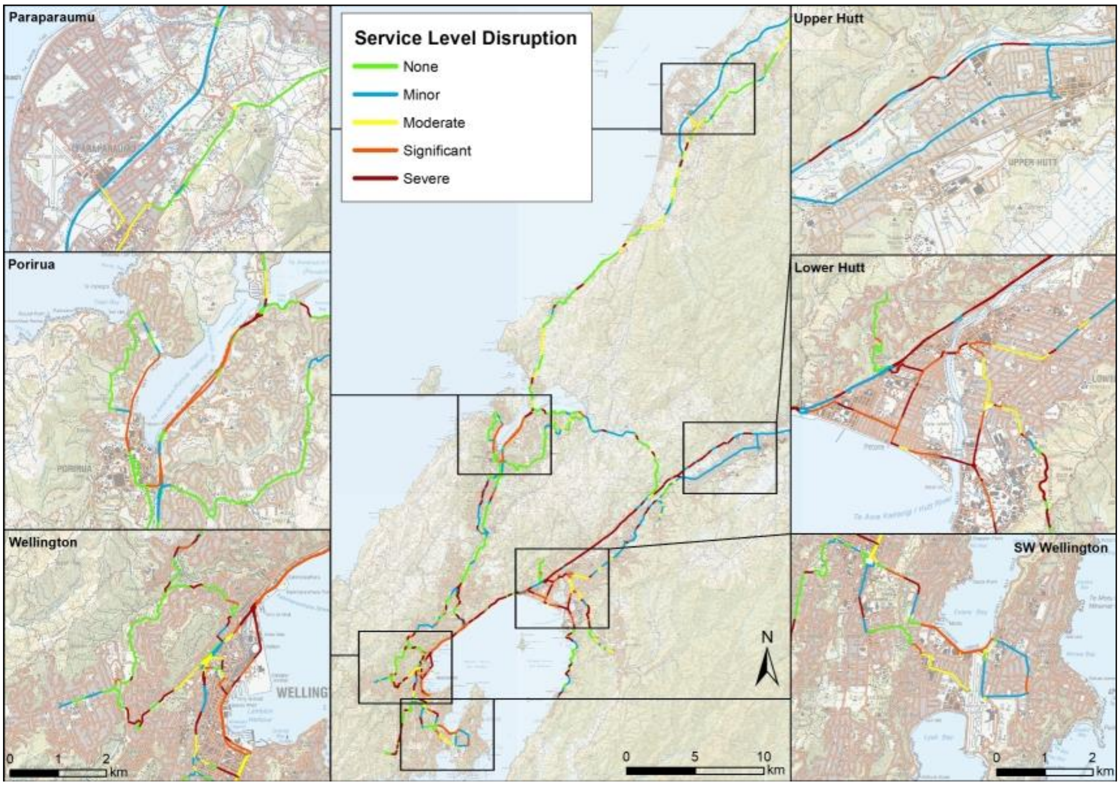


Fig. 6 – Potential road service disruption (base case) under the Wellington Fault earthquake scenario

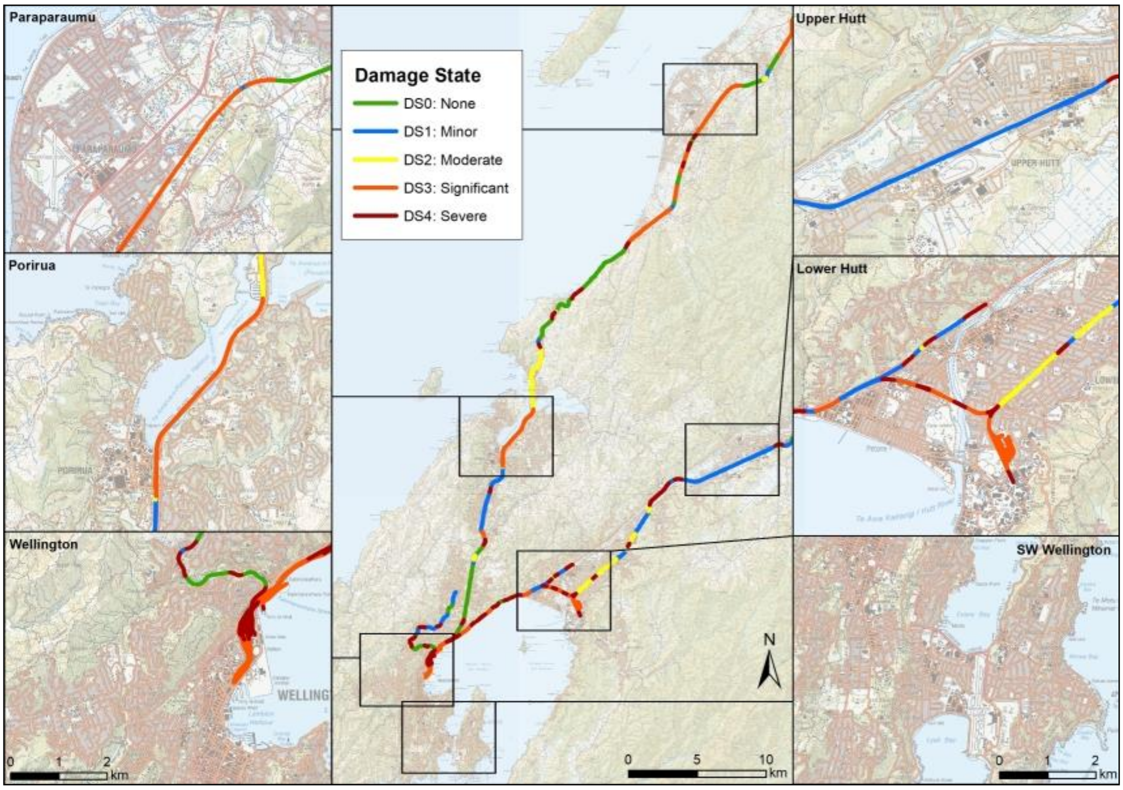


Fig. 7 – Potential damage to rail network (base case) under the Wellington Fault earthquake scenario

Table 1 – Estimated outage times (in days) for road access between transportation zones (Fig. 3) for Base Case. Values outside and inside the brackets are respectively for response and recovery levels of service

Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1																								
2	7 (28)																							
3	7 (28)	5 (21)																						
4	7 (28)	3 (21)	5 (21)																					
5	7 (28)	3 (21)	5 (21)	2 (14)																				
6	7 (28)	3 (21)	5 (21)	2 (21)	2 (21)																			
7	7 (28)	3 (21)	5 (21)	2 (14)	1 (7)	2 (21)																		
8	7 (97)	7 (97)	7 (97)	7 (97)	7 (97)	7 (97)	7 (97)																	
9	7 (97)	7 (97)	7 (97)	7 (97)	7 (97)	7 (97)	7 (97)	3 (93)																
10	13 (103)	13 (103)	13 (103)	13 (103)	13 (103)	13 (103)	13 (103)	13 (103)	13 (103)															
11	10 (100)	10 (100)	10 (100)	10 (100)	10 (100)	10 (100)	10 (100)	10 (100)	10 (100)	13 (103)														
12	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)													
13	10 (104)	10 (104)	10 (104)	10 (104)	10 (104)	10 (104)	10 (104)	10 (104)	10 (104)	13 (104)	14 (104)	14 (104)												
14	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	12 (102)	14 (104)											
15	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)										
16	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)									
17	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	7 (21)								
18	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	90 (180)	40 (180)	40 (180)							
19	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	7 (21)	3 (14)	40 (180)						
20	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	21 (30)	21 (30)	40 (180)	21 (30)					
21	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	10 (49)	10 (49)	40 (180)	10 (49)	21 (49)				
22	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	90 (120)	10 (42)	10 (42)	40 (180)	10 (42)	21 (42)	10 (49)			
23	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	90 (138)	30 (138)	30 (138)	40 (180)	30 (138)	30 (138)	30 (138)	30 (138)		
24	21 (28)	21 (28)	21 (28)	21 (28)	21 (28)	21 (28)	21 (28)	21 (97)	21 (97)	21 (103)	21 (100)	21 (104)	21 (104)	21 (104)	21 (104)	90 (120)	90 (120)	90 (180)	90 (120)	90 (120)	90 (120)	90 (120)	90 (138)	

4.2 Improved Resilience Case

In this case the same earthquake scenario was assumed to strike the same networks, but with specific infrastructure investments made, such as new roads constructed, or improved rail structures. As part of the PBC, series of workshops were held with all the participating lifeline organisations (17 in total) and government representatives to collectively identify problems to be addressed, discuss the potential benefits that could be gained by improving infrastructure resilience, and to define investment objectives. Over a hundred resilience improvement options (covering all the lifelines in the scope) were initially put forward, which after critical assessment, the short-listed projects were put into three groups (lower, higher and preferred investment level programmes). In total three sets of modelling were undertaken to evaluate the economic benefit each investment programme offered over the base case. At every stage of short-listing the projects due recognition was given to the importance of infrastructure interdependencies and to ensure any investment was focussed on delivering the best results for building the resilience for the region and not necessarily just for each individual utility.

The preferred programme of works put forward in the WeLG PBC comprised a total of twenty-five projects (across the fuel, transport, electricity, telecommunications, water and gas networks) sequenced to be phase-delivered over a twenty-year period. The proposed timelines and indicative costs to deliver the roading and rail projects over the twenty years is shown in Table 2 (also see Fig. 8).

Table 2 – Proposed resilience investment projects for road* and rail networks.

Project	**Significance**
SH58/Haywards Resilience Improvements from Transmission Gully to Hutt Valley Phase 1: 0-7 years Cost est. (2019): $24m	This project includes stabilisation of slopes above SH58 at Haywards Hill from SH2 to summit. This project will provide alternate access through to Porirua from the Hutt Valley. This will allow residents of the Hutt Valley to travel through to Wellington City via Porirua (and vice versa) in the likely event that access along the SH2 coastal road (depicted by larger X in Fig. 8) is cut off. This project will also provide access for fuel trucks to transport fuel from Petone through the region. The safety improvements element of this project has been committed.
Taita Gorge Access – strengthening road network Phase 1: 0-7 years Cost est. (2019): $2.5m	This project will involve stabilising slopes and upgrading the walls supporting the Eastern Hutt road. This project will help prevent collapse of the Eastern Hutt Road into the Hutt River, maintaining access up the eastern side of Taita Gorge following an event. This project also helps maintain access to Hutt Hospital.
Wadestown to Johnsonville – seismic strengthening Phase 1: 0-7 years Cost est. (2019): $20m	This project involves strengthening the retaining walls and engineering of some major uphill slopes on Churchill Drive, Blackbridge Road and Wadestown Road, which service Bowen Hospital. This route is likely to be one of the first access routes open for ambulances to get through to Bowen Hospital. This route also provides access through to critical Wilton Substation for inspection and repair following an event and provides a potentially important secondary route towards Wellington's CBD.
Improve resilience of airport connectivity to city network via Newtown Phase 1: 0-7 years Cost est. (2019): $10m	This project involves emergency response planning for the roads alongside the Hospital It would also involve potential interventions around the Mt Victoria Tunnel portals to protect from landslides either side and reduce the tunnel outage time. This project provides access from Wellington Airport through to the CBD should the Evans Bay route be blocked due to landslides. This provides access through to the airport for personnel, for both the response and recovery periods.
Better engineered road links to existing RORO Terminal and port area Phase 1: 0-7 years Cost est.: $71m	This project involves mitigation measures to potential liquefaction on Aotea Quay following a seismic event, seismic upgrading of the Skew Rail Bridge and an emergency ramp from SH1 to the roll-on roll-off (RORO) area at the port. Proposed works will help provide quicker access to the core port area and to RORO facility.

Project	Significance
New road: Petone to Grenada Phase 2: 8-14 years Cost est.: Capital cost: $250 million to $2,200 million (2018 re-evaluation summary report), however for the WeLG PBC report the figure of $1,062 million was used.	This project includes a new road link from Hutt Valley to SH1. It will include slope stabilisation measures and basic resilience enhancements to increase the chance of a link between the two corridors following a 7.5 Wellington Fault earthquake event. This project was re-evaluated by the Waka Kotahi - NZ Transport Agency in 2018, more detail on this can be found in [6]. This project provides significant benefits to communities in terms of access into and out of the Hutt Valley. It also improves the lifeline restoration times of other lifelines which require road access to refuel and repair.
Cross Valley Link (new road) – SH2 to Seaview Phase 2: 8-14 years Cost est. (2019): $65m	From a resilience perspective - given the criticality of fuel to the recovery of the Wellington Region following a major event - this link would provide a stronger connection between the fuel terminals at Seaview with the transport network and the rest of the region.
Middleton Road retaining walls upgrade Phase 3: 15-20 years Cost est. (2019): $50m	This project involves the strengthening of retaining walls for gas main protection or alternatively the re-laying of the gas main on the uphill side of the slope. Minor improvements to batter slopes may also be included to reduce the amount of material likely to slide during an event, and therefore reduce the recovery time.
Rail seismic upgrade of slopes and structures Proposed work evenly split between Phase 1 & 2 Cost est. (2019): $100m (notional)	Seismic upgrading of structures and slopes along the NIMT, Hutt Valley Line, Upper Hutt Line and Wairarapa Line (Fig. 3). This project would allow freight and commuter trains to be back running earlier and with greater reliability.

*funding/scope for the NZTA projects are indicative only and full assessment/investigation/design may change the extent/cost of the initiative(s)

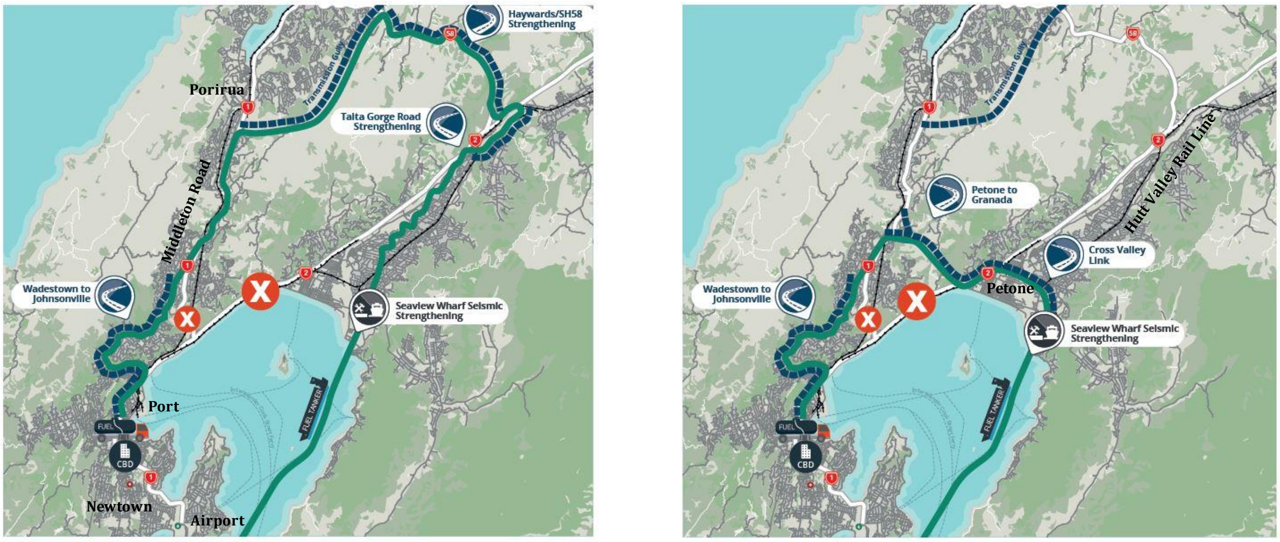


Fig. 8 – Proposed roading initiatives to improve regional resilience. *Original map credit: Aurecon*

Due to the nature of the proposed intervention projects it was decided after consultation with the respective roading teams that no explicit damage modelling of these projects was necessary. It was assumed that the proposed works would undergo detailed engineering assessments, geotechnical investigations, and would meet current standard requirements etc., and risks identified would be addressed accordingly. The effect of the proposed roading projects in restricting damage to the improved network was therefore qualitatively assessed and restoration times estimated for the two levels of service (Table 3). Specific details relating to the rail initiative are yet to be scoped; however, the proposed investment can be anticipated to restrict the damage to the network and help reduce the outage times for rail services. In the preferred investment programme, it was estimated that freight services would return to reduced levels of service from nine months following the earthquake, then gradually returning to pre-earthquake service level by the end of 3 years. Return of full passenger services was expected to take about 39 months following the earthquake.

Table 3 – Estimated outage times (in days) for road access between transportation zones (Fig. 3) for the Preferred Investment Programme. Values outside and inside the brackets are respectively for response and recovery levels of service

Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1																								
2	7 (28)																							
3	7 (28)	5 (21)																						
4	7 (28)	3 (21)	5 (21)																					
5	7 (28)	3 (21)	5 (21)	2 (14)																				
6	7 (28)	3 (14)	5 (21)	2 (21)	2 (21)																			
7	7 (28)	3 (21)	5 (21)	2 (14)	1 (7)	2 (21)																		
8	7 (60)	7 (60)	7 (60)	7 (60)	7 (60)	7 (60)	7 (60)																	
9	7 (93)	7 (93)	7 (93)	7 (93)	7 (93)	7 (93)	7 (93)	3 (93)																
10	13 (103)	13 (103)	13 (103)	13 (103)	13 (103)	13 (103)	13 (103)	13 (103)	13 (103)															
11	7 (60)	7 (60)	7 (60)	7 (60)	7 (60)	7 (60)	7 (60)	5 (40)	5 (93)	13 (103)														
12	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)													
13	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)												
14	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	7 (102)	14 (104)											
15	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)	14 (104)										
16	15 (28)	15 (21)	15 (21)	15 (20)	15 (20)	15 (21)	15 (20)	15 (60)	15 (93)	15 (103)	15 (60)	15 (104)	15 (104)	15 (104)	15 (104)									
17	15 (28)	15 (21)	15 (21)	15 (20)	15 (20)	15 (21)	15 (20)	15 (60)	15 (93)	15 (103)	15 (60)	15 (104)	15 (104)	15 (104)	15 (104)	7 (10)								
18	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)	40 (180)							
19	15 (28)	15 (21)	15 (21)	15 (20)	15 (20)	15 (21)	15 (20)	15 (60)	15 (93)	15 (103)	15 (60)	15 (104)	15 (104)	15 (104)	15 (104)	7 (14)	3 (14)	40 (180)						
20	7 (28)	3 (21)	5 (21)	3 (14)	3 (14)	3 (21)	3 (14)	7 (60)	7 (93)	13 (103)	7 (60)	14 (104)	14 (104)	14 (104)	14 (104)	15 (20)	15 (20)	40 (180)	15 (20)					
21	15 (39)	15 (39)	15 (39)	15 (39)	15 (39)	15 (39)	15 (39)	15 (60)	15 (93)	15 (103)	15 (60)	15 (104)	15 (104)	15 (104)	15 (104)	7 (39)	7 (39)	40 (180)	7 (39)	15 (39)				
22	15 (32)	15 (32)	15 (32)	15 (32)	15 (32)	15 (32)	15 (32)	15 (60)	15 (93)	15 (103)	15 (60)	15 (104)	15 (104)	15 (104)	15 (104)	7 (32)	7 (32)	40 (180)	7 (32)	15 (32)	7 (39)			
23	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	30 (138)	40 (180)	30 (138)	30 (138)	30 (138)	30 (138)		
24	21 (28)	21 (28)	21 (28)	21 (28)	21 (28)	21 (28)	21 (28)	21 (60)	21 (93)	21 (103)	21 (60)	21 (104)	21 (104)	21 (104)	21 (104)	21 (28)	21 (28)	40 (180)	21 (28)	21 (28)	21 (39)	21 (32)	30 (138)	

5. Conclusions

New Zealand is a sovereign country in the southwestern Pacific Ocean that is prone to a range of natural hazards. The country has experienced some large earthquakes in recent times that have tested the resilience of its built environment and communities. These indicate that measures are required to be taken to reduce the impact from, and respond to, and recover quickly from, future disasters. This paper discussed one such major initiative proposed to improve the resilience of lifeline utility services in Wellington (the capital of New

Zealand) and its surrounding cities. As part of this project, damage and service outage modelling on ten different lifeline utilities were conducted, and the assessment approach taken was explained in this paper for the road and rail networks in the region. It was demonstrated that by making targeted and integrated infrastructure investments before the next major earthquake in the region, physical damage to the networks and disruption to the services these networks provide can be reduced, thereby resulting in lesser economic disruption. The temporal service outage tables (that show the times to access between suburbs) generated from this work formed an essential input to evaluate and demonstrate the impact of the proposed resilience investments on regional and national economies.

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7. References

[1] Wotherspoon LM, Palermo A, Holden C (2017): The 2016 Mw7.8 Kaikoura earthquake: an introduction. Bulletin of the New Zealand Society for Earthquake Engineering, 50(2), i-iv. http://www.nzsee.org.nz/db/Bulletin/Archive/50(2)000i.pdf

[2] Davies AJ, Sadashiva VK, Aghababaei M, et al. (2017): Transport infrastructure performance and management in the South Island of New Zealand, during the first 100 days following the 2016 Mw 7.8 "Kaikoura" earthquake. Bulletin of the New Zealand Society for Earthquake Engineering, 50(2), 271-299. http://www.nzsee.org.nz/db/Bulletin/Archive/50(2)0271.pdf

[3] Bulletin of the New Zealand Society for Earthquake Engineering, 43(4), December 2010. http://www.nzsee.org.nz/bulletin_index/43_4.htm

[4] Bulletin of the New Zealand Society for Earthquake Engineering, 44(4), December 2011. http://www.nzsee.org.nz/bulletin_index/44_4.htm

[5] Stats NZ. [accessed December 2019]. http://archive.stats.govt.nz/Census/2013-census/profile-and-summary-reports.aspx

[6] Wellington Lifelines Group (2019): Protecting Wellington’s Economy Through Accelerated Infrastructure Investment Programme Business Case. Revision 3.

[7] Sadashiva VK, Nayyerloo M, Williams J, Heron DW, Uma SR, Horspool NA, Buxton R, Lin S-L, Lukovic B, King AB, Berryman K, Daly M (2020): Potential benefits of implementing water network resilience projects in Wellington region of New Zealand. Paper No. C002641. 17WCEE, 17th World Conference on Earthquake Engineering, Sendai, Japan.

[8] Sadashiva VK (2018): Wellington City Council earthquake risk assessment – infrastructure and general buildings: 2018 update. Consultancy Report 2018/39, GNS Science, Lower Hutt, NZ.

[9] King AB, Sadashiva VK, Dellow GD, Paulik R, Bell R, Smart G, Wadhwa S, Matcham I (2015): Highway Network Risk Evaluation Tool – Proof of Concept, GNS Science Consultancy Report 2015/223. 93 p.

[10] Sadashiva VK, King AB, Matcham I (2017): Exploring a risk evaluation tool for New Zealand State Highway Network National Resilience Project. 16th World Conference on Earthquake Engineering, 16WCEE, Santiago, Chile.

[11] Opus (2012): Wellington Region road network earthquake resilience study. Report No. GER 2012-21.