Resilience of State Highways

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September 2016

Issue 1

Recommended Regional Assessment Methodology for Low Frequency Hazard Exposure

NZ TRANSPORT AGENCY
WAKA KOTAHI

New Zealand Government

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CONTENTS

TABLES

ILLUSTRATIONS

1. INTRODUCTION

The New Zealand Transport Agency (the Agency) is developing its strategy to understand and enhance the resilience of its state highway network to natural hazards. As part of this strategy, the Agency has engaged Opus International Consultants (Opus) to assess the resilience of the national state highway network for low frequency, high impact natural hazards. The scope of the national resilience assessment comprises 2 parts, as follows:

Part 1: National resilience framework

A. Review previous relevant work on the assessment of the resilience of the road networks in New Zealand.

B. Develop a methodology for a national level assessment of the resilience of the state highway network.

C. Implement the national resilience assessment methodology to assess the resilience of the state highway network at national level.

The results of the national level screening will inform the development of Strategic Business Cases.

Part 2: Regional resilience framework

Part 2 consists of development of a methodology for detailed corridor assessments at regional level.

This report presents the methodology developed for the regional level assessment of the resilience exposure of the state highway network for low frequency, high impact natural hazards. This framework is consistent with the national approach but uses more detailed regional information. This allows the resilience of the state highway assets to be assessed at a more detailed regional level. The results of these assessments will inform the development of Programme Business Cases.

2. OBJECTIVES

The objectives of the regional assessment process are:

- Enable assessment of the resilience exposure of state highway corridors to low frequency, high impact natural hazards at a more detailed level than the national assessment, so that it can be used for the development of programme business cases for corridors and for planning resilience enhancement and network asset and emergency management;
- Provide a consistent basis for assessment of the resilience for the state highways in all the regions;
- Enable detailed understanding of the resilience of the network, particularly sections of corridors with poor resilience;
- Underpin the evaluation of gaps in resilience (desired resilience vs current resilience);
- Provide outputs suitable for the development of strategic responses and be able to be used for development of resilience enhancement measures (including emergency response planning);
- Provide a toolkit, including a process map and appropriate evidence/references that could be used in the process, and which has flexibility for adaptation/innovation for specific issues.

These objectives have provided the basis of the development of the regional assessment methodology for resilience exposure to low frequency, high impact events.

3. RESILIENCE

Resilience is the ability to readily recover and return to original form from adversity.

Knowledge of the resilience of the road network in natural hazard events is important to understand the impact on society – the people, emergency services, economic activity etc. This would also enable the expected resilience to be compared against desired level of service targets, and help develop resilience enhancement measures.

The resilience of roads is dependent on the loss of quality or serviceability, and the time taken to bring the road back into its original usage state. This is shown conceptually in Illustration 1 (after Brabhaharan, 2006). The smaller the shaded area, the more resilient is the road/network. The greater the area, the poorer is the resilience.

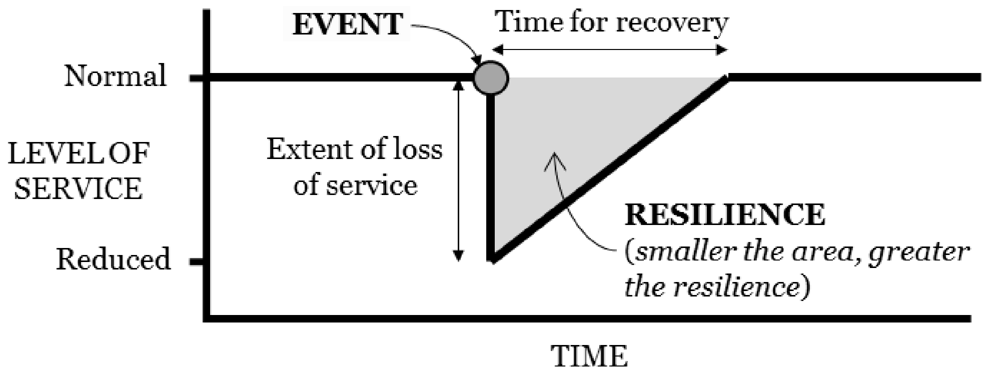

Illustration 1 Resilience of network

"Resilience States" representing the performance of the road network have been developed by Brabhaharan *et al.* (2006) to consider the impact of various natural hazards on the road network on a similar basis. These states are summarised in Table 1.

Table 1 Resilience states

RESILIENCE STATE	DESCRIPTION OF STATE
Damage state	Damage State represents the severity of damage to the road and represents the damage and cost of damage repairs.
Availability state	Availability 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 degree of access on a link after an event.
Outage state	Outage State indicates the duration over which the road will be in the Availability State above. This gives an indication of the duration of loss or reduced access in links along the road network.

The damage state is used to consider the potential cost of the effects, but is not considered directly useful to evaluate the resilience of the network, and therefore will not be used.

4. RESILIENCE METRICS

It is important to use appropriate metrics that are meaningful, to assess the resilience of the state highway network. State highways provide access for communities and businesses, and in evaluating their resilience it is important to represent the availability or lack of access in the event of natural hazards. Therefore it is appropriate to use metrics that reflect the level of service, and be understandable to stakeholders. This enables everyone to relate to the metrics that represent the performance of the state highway network.

For the successful execution of the project at both national and regional levels, it is advisable to select metrics that have been proven in the assessment of resilience, as well as used in initiatives to address resilience gaps through emergency preparedness or appropriate mitigation measures.

Metrics used for the national level assessment of the state highway network were presented in the national assessment methodology report (Brabhaharan and Mason, 2016). The metrics used at a regional level should be consistent with those used at the national level, as well as being able to underpin decision making relating to actions to enhance the resilience of the state highway corridors and related local road routes.

The two key dimensions of resilience are (refer Illustration 1):

- Reduction in access as a consequence of the event, and hence the degree of access available, and
- Time taken for access to be restored, or the duration of access impairment.

Therefore, the resilience metrics have been used to represent these two dimensions, through the resilience states developed by Brabhaharan *et al*. (2006) of:

- Availability State – level of access after the event, representing the level of service, and
- Outage State – the duration of reduced access at the above availability state.

A '*disruption state*' combining the availability state and outage states was used in the national level screening, to provide a single parameter indicating the level of disruption caused by the hazard event at each road section. This parameter was useful at a national level to help identify areas with poor resilience, however for more detailed assessment at the regional level this single parameter may be less meaningful than the two resilience states of availability and outage.

These availability states are represented as the following levels given in Table 2 and Table 3, modified after Brabhaharan (2006).

Table 2 Availability state

AVAILABILITY LEVEL	AVAILABILITY STATE	AVAILABILITY DESCRIPTION
1	Full	Full access (perhaps with driver care).
2	Poor	Available for slow access, but with difficulty by normal vehicles due to partial lane blockage.
3	Single Lane	Single lane access only with difficulty due to poor condition of remaining road.
4	Difficult	Road accessible single lane by only 4x4 off road vehicles.
5	Closed	Road closed and unavailable for use.

Table 3 Outage state

OUTAGE LEVEL	OUTAGE STATE	OUTAGE DESCRIPTION
1	Open	No closure, except for maintenance
2	Minor	Condition persists for up to 1 day
3	Moderate	Condition persists for 1 day to 3 days
4	Short term	Condition persists for 3 days to 2 weeks
5	Medium term	Condition persists for 2 weeks to 2 months
6	Long term	Condition persists for 2 months to 6 months
7	Very long term	Condition persists for >6 months

5. REGIONAL ASSESSMENT METHODOLOGY

The approach to assess the resilience exposure of state highway routes at a corridor or regional level is summarised in Illustration 2. This is based on the approach developed by Brabhaharan *et al.* (2001, 2006), and is consistent with the approach developed for the national level resilience assessment (Brabhaharan & Mason, 2016). More detailed descriptions of each step in the assessment process are given below.

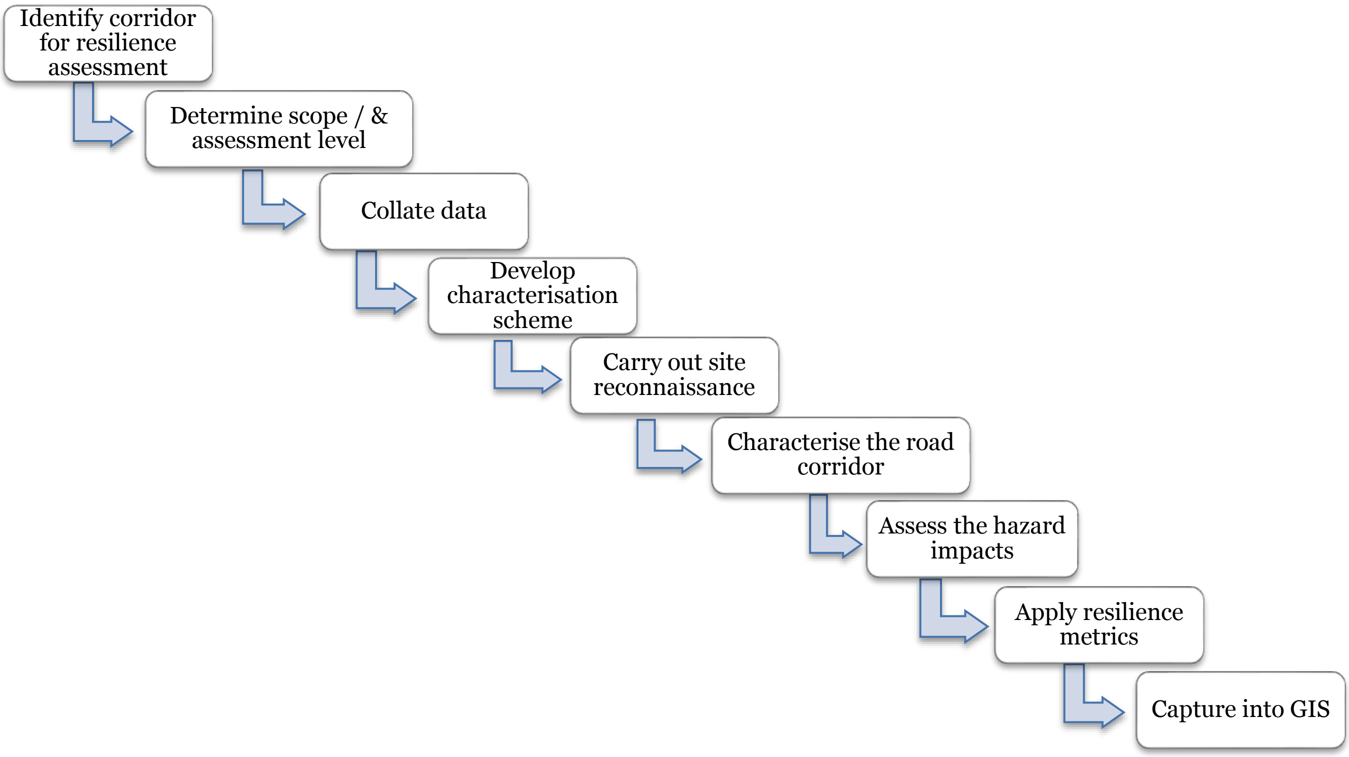

Illustration 2 Process map for assessment of road resilience at regional level

The steps in the resilience assessment methodology are described in more detail below.

1. Identify corridor for resilience assessment

Purpose: Identify corridors forming the regional network which require a more detailed assessment of resilience, because of the criticality of the routes, understanding of network functionality or because of suspected low resilience from national level screening.

Process: Use the results of the national resilience screening to identify corridors with suspected low resilience, and routes that are critical to the functioning of the regional network. The resilience should be considered across all relevant hazard types.

Example:

The map of disruption state in the national level screening shows sections of low resilience (red, brown and amber) of SH2 between Te Marua and Ngauranga (Illustration 3), where the road lies between steep hillslopes and the Hutt River. The map shows susceptibility to rainfall-induced landslides, debris flows, flooding, scour/underslips, and earthquake-induced landslides and liquefaction. The road also crosses the active Wellington Fault at Moonshine Bridge and lies in close proximity to the fault trace between Upper Hutt and Melling. This highlights the need for further assessment considering the availability and outage states, for this critical route in the Wellington Region.

Illustration 3 Disruption state for earthquakes hazards on SH1 and SH2, Silverstream to Wellington

2. Determine scope and assessment level

Purpose: Confirm the scope and extent of the assessment required.

Process: Determine the location and length of the corridor/s of interest, the natural hazards of relevance to the study, return periods of the principal hazards, any additional corridors for possible inclusion in the study (e.g. local roads that provide critical alternative routes), and any other factors to be included in the assessment.

The levels of natural hazards suitable for the resilience assessment, and which are consistent with common design levels, are summarised in Table 4.

Table 4 Hazard event levels for resilience assessment

HAZARD	RECURRENCE INTERVAL FOR ASSESSMENT OF RESILIENCE	BRIDGE MANUAL
Storm / flooding	1 in 100 years	1 in 100 years
Earthquake	1 in 1,000 years	1 in 500 to 1 in 2,500 years
Volcanic eruption	1 in 1,000 years	-
Tsunami	1 in 1,000 years	-

These levels may need to be varied depending on the hazard data available for these assessments. Also it may be in some situations be appropriate to use specific scenarios (e.g. characteristic Wellington Fault or Alpine Fault rupture scenarios) rather than recurrence intervals indicated in Table 4. Similarly, it may be appropriate to use a range of return periods for a specific hazard to determine the sensitivity of the corridor's vulnerability to that hazard. This should be discussed and agreed with the local regional office of the Transport Agency.

3. Collate data

Purpose: Collate available data necessary for use in the resilience assessment.

Process:

a) Overlay available data on national resilience screening map and determine where gaps in data are;

b) Review the level of the currently held data (e.g. national level data vs regional level data of greater definition)

c) Ascertain what data is available but not currently held;

d) Collate required additional data available for the region;

e) Identify if new data is required to be collected.

Data collated as part of the national level assessment is listed in Table 5 below. Some of the data collected for the national study would be suitable for use in the regional assessment (e.g. state highway spatial data, including ONRC classification) as shown in the table.

For the regional assessment, more detailed data would be required for specific hazards. The following datasets listed in Table 6 are examples of the types of data that might be required for regional-level assessments that were not collected or were not available at the time of the national screening.

The coverage and levels of detail for these types of data is likely to be highly variable across the country, and consequently it may be necessary to carry out investigations to provide specific information at a corridor level. For example, depending on the particular corridor, it may be necessary to carry out lidar or UAV surveys to get detailed topographic information for slope assessments or flood hazard studies, or geotechnical investigations to enable liquefaction analyses for critical structures.

It may be necessary to obtain advice from GNS Science, NIWA or university research departments on the earthquake, flooding, volcanic or tsunami hazards.

Table 5 Data and sources collated for national resilience screening

DATA TYPE	DATASET	SOURCE	LEVEL OF APPLICABILITY
Road assets	• State highway centreline (with ONRC data)	Transport Agency	National & regional
	• State highway corridor video	Transport Agency	National & regional
Geography & geology	• Topography contours 20 m (part 10m)	LINZ	National
	• Digital elevation model (DEM) 8 m	LINZ	National
	• NZ Land Resource Information System: – Soil/rock lithology – Erosion type/severity – Slope angle class	Landcare Research	National
	• Geology	GNS Science	National & regional
	• Erosion susceptibility & limiting factors	MfE	National
Storms, floods & coastal hazards	• 1% AEP 24 hour rainfall depths	NIWA	National & regional
	• River Environment Classification (REC)	NIWA	National
	• Flood hazard screening for bridges	Transport Agency	National & regional
	• Flood hazard maps	Local authorities	Regional
	• Sea level rise predictions	MfE, IPCC	National & regional
	• Coastal inundation maps (variable coverage)	Regional councils	Regional
Earthquake hazards	• Earthquake hazard maps: – Active faults – Ground shaking – Liquefaction	GNS Science, regional councils	National & regional (variable coverage)
	• Seismic screening of bridges	Transport Agency	National & regional
Volcanic eruption	• Volcanic hazard maps: – Pyroclastic ash fall (tephra) – Pyroclastic & lava flow – Lahar	GNS Science, regional councils, universities	National & regional
Tsunami	• Tsunami hazard maps	GNS Science, NIWA, regional councils	National & regional
	• Tsunami impacts on roads	Wellington lifelines group, universities	National

Table 6 Datasets required for regional resilience assessments

DATA TYPE	DATASET	SOURCE
Road assets	• Bridge, retaining wall and culvert assessment reports	NZ Transport Agency
	• Alternative route mapping, including any hazard, risk or resilience studies (e.g. local road networks)	NZ Transport Agency
Geography & geology	• Detailed topography/terrain data (e.g. lidar or 1 m contour data)	Local authorities/regional councils; NZ Transport Agency
Storms, floods & coastal hazards	• Stopbank/flood protection assets, including: – Level of protection (design flood event) – Date of construction – Proximity to road (both vertically and horizontally) – Resilience assessments for Councils	Local authorities/regional councils
	• Flood models, including the extent and depth of inundation and incorporating assessment of climate change impacts	Local authorities/regional councils
	• Coastal erosion assessments (incorporating sea level rise impacts)	Local authorities/ regional councils, NIWA
	• Slope failure hazard studies (e.g. rock fall hazard ratings, landslide inventories, preventative maintenance records)	NZ Transport Agency, regional councils
	• History of road closures, location, duration, and cause	NZ Transport Agency
Earthquake hazards	• Regional seismicity studies (e.g. Illustration 4)	GNS Science, universities, NZ Transport Agency
	• Active fault studies (e.g. Illustration 5)	GNS Science, universities, EQC, NZ Transport Agency
	• Liquefaction ground damage assessments, supplemented by available geotechnical investigations in sensitive areas e.g. interchanges or bridges (e.g. Illustration 6)	Regional councils, EQC, NZ Transport Agency
Volcanic hazards	• Volcanic hazard/risk studies	Local authorities, GNS Science, universities
Tsunami hazards	• Tsunami inundation/evacuation maps (e.g. Illustration 7) • Assessment of bridge vulnerability to tsunami damage (ongoing research)	CDEM, NIWA, GNS Science, universities, regional councils

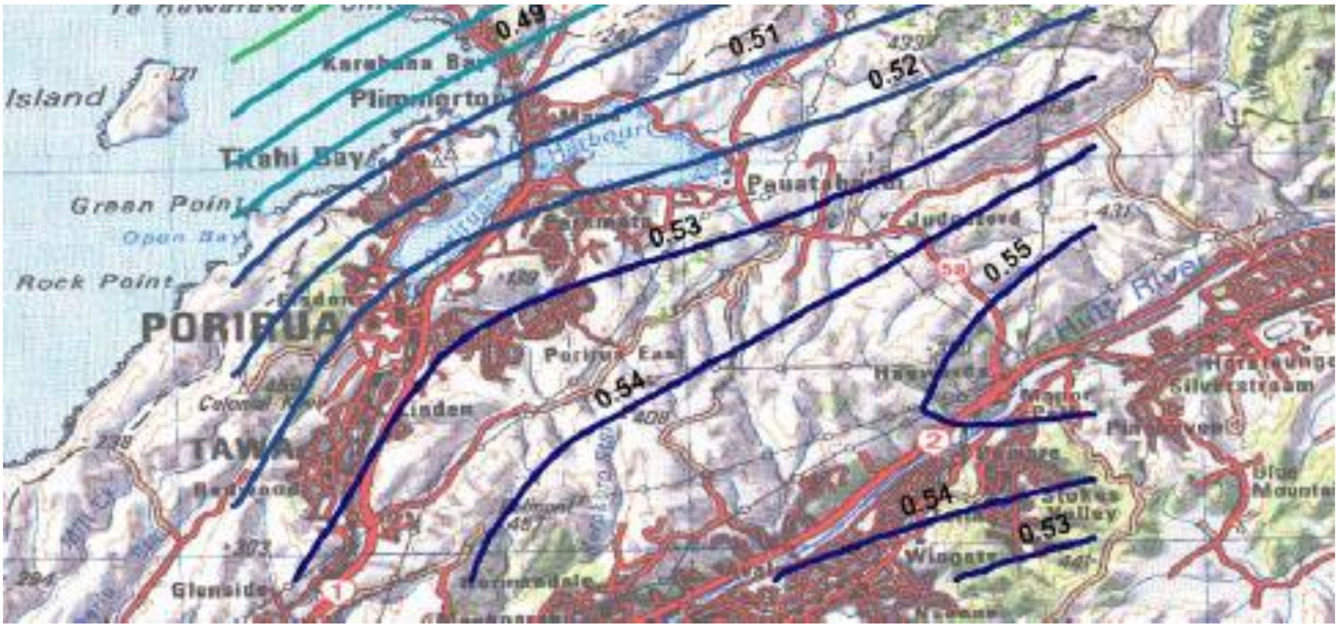

Illustration 4 Contours of 500-year return period peak ground accelerations for the upper Hutt Valley and Porirua areas (McVerry and Destegul, 2008).

Illustration 5 Locations of active faults in the Wellington and Hutt Valley areas (after Begg and Mazengarb, 1996).

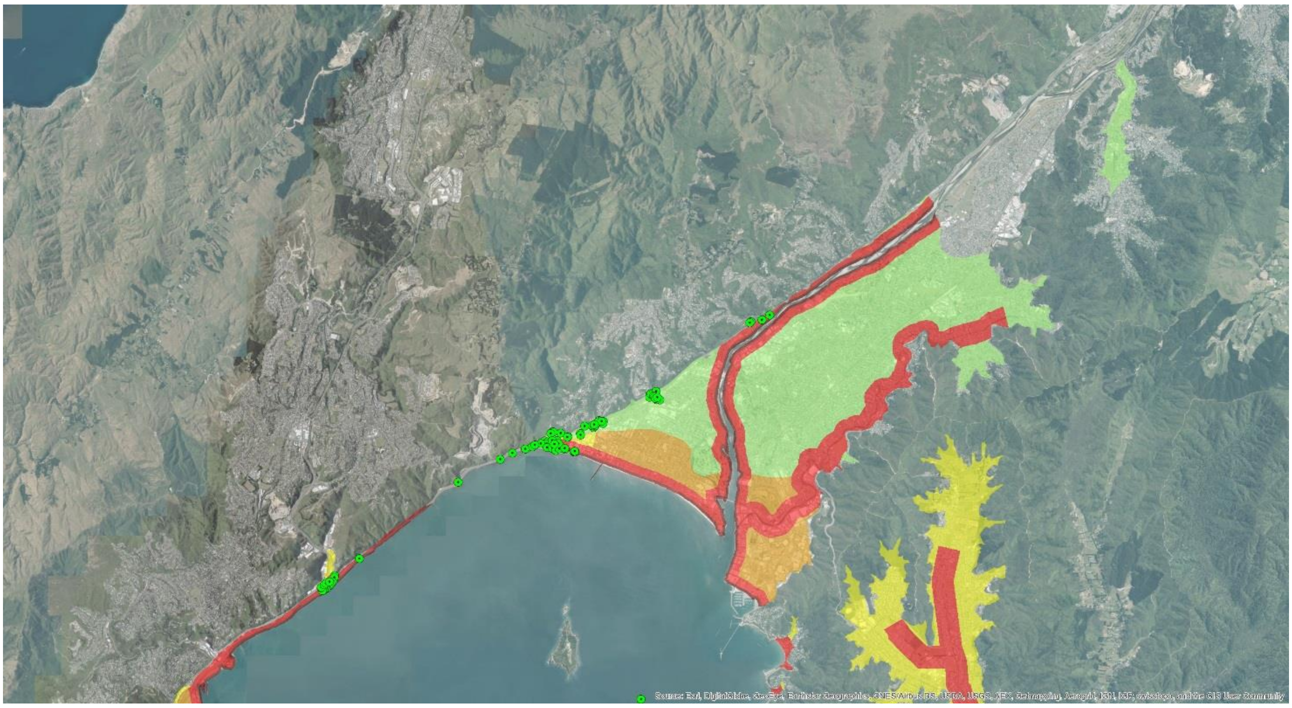

Illustration 6 Liquefaction ground damage hazards in the Wellington and Hutt Valley areas (Greater Wellington Regional Council, http://mapping.gw.govt.nz/gwrc), with the green dots showing locations of recent geotechnical investigations in the Petone to Ngauranga area.

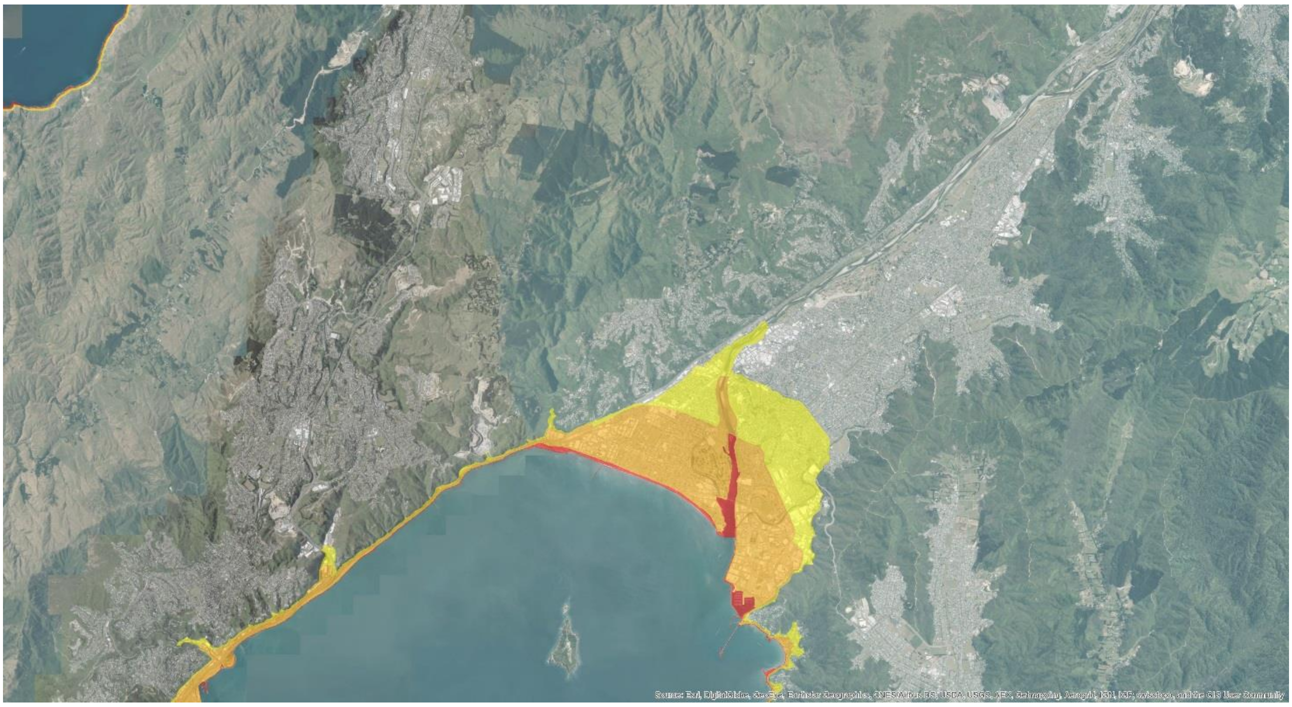

Illustration 7 Tsunami hazard map for the Wellington and Hutt Valley areas (Greater Wellington Regional Council, http://mapping.gw.govt.nz/gwrc).

4. Develop Road Characterisation Scheme

Purpose: The hazard exposure of the road will vary due to changes in the geological and geomorphological environment along the corridor. Therefore the road/s need to be segmented to the length of each hazard impact (based on changes in road environment and hazard exposure). This enables definition and differentiation of the variability of hazard impacts along the corridor.

Process:

a) Define categories to be used for classifying the road corridor, considering factors such as:

- Geology, groundwater, slope angles;
- Erosion, flooding and scour potential;
- Potential slope failures;
- Liquefaction potential;
- Fault rupture hazard;
- Volcanic hazard vulnerability (e.g. lahar flow path);
- Structures (bridges, tunnels and retaining walls), by types, design and condition;
- Observed impacts from damage due to natural hazards, and likely extent of impacts on highway access.

The characterisation should define a series of categories that differentiate the terrain, road environment, structures, hazards etc., and should include a description of the anticipated types of damage. There should be sufficient detail in the characterisation scheme to enable differentiation of individual road segments where types or levels of damage may differ (e.g. subdividing road segments through hilly terrain on the basis of slope height, slope angle, geology, stability, failure mechanisms, proximity of slope to road etc.). Parameters to be used in the characterisation framework are given in Table 7 below.

Table 7 Characterisation framework

TERRAIN / ENVIRONMENT	SCALE / TYPE	FAILURE TYPE / SIZE	CONSEQUENCES TO ROAD	REPAIR ISSUES TO CONSIDER
▪ Flat to rolling ▪ Slopes above road ▪ Cut slopes ▪ Slopes below road ▪ Embankments ▪ Gullies ▪ Along Streams ▪ Along coast ▪ Retaining walls ▪ Bridges ▪ Tunnels	▪ Height ▪ Geology ▪ Stability ▪ Type ▪ Condition	▪ Small ▪ Medium ▪ large	▪ Inundation ▪ Debris ▪ Scour ▪ Deformation ▪ Cracking ▪ Shoulder closure ▪ Part lane closure ▪ Half closure ▪ Full closure	▪ Clearance ▪ Stabilisation ▪ Rockfall protection ▪ Embankment ▪ Culvert ▪ Retaining wall ▪ Bridge ▪ Design ▪ Construction

Test and verify the applicability of the characterisation scheme to the road corridor, using the information collected, a reconnaissance drive-over, review and update as required.

5. Site Reconnaissance Mapping

Purpose: Field mapping of the route to better understand the terrain and hazards.

Process: Carry out field mapping, comprising drive over and walkover mapping of the route/s, to better understand the terrain and the potential impact of hazards on the state highway, and to refine and update the characterisation mapping.

During reconnaissance the assessor should look out for a distance either side of the road, to a distance where the hazards could potentially affect the road corridor.

In particular, some of the things to look out for are:

- Terrain
- Slopes
- Geology and groundwater (seepages)
- Evidence of past failures
- Debris sources
- Floodways and water courses and relationship to road
- Culverts and inlet / outlet conditions
- Structures, their type, condition and stability.
- Road berms and separation of potential hazards from the road lanes.

6. Characterise the Road Corridor

Purpose: Associate road characterisation categories to segments of the road, so that the resilience of segments of the road with different physical and vulnerability characteristics can be assessed.

Process: Segmentation and determination of the category of each segment, using the road vulnerability characterisation scheme developed. The characterisation should be based on the hazard information gathered, site reconnaissance mapping and review of relevant topographical and aerial maps along the route.

Review characterisation scheme and refine as necessary to facilitate effective characterisation of the whole chosen route / network.

7. Assess hazard impacts

Purpose: Associate road characterisation categories to potential levels of damage for the range of return periods by hazard type.

Process: Determine potential levels of damage based on the triggering hazard and anticipated failure mechanism, in terms of the road availability (or lack of access) that results from the potential failure.

Given that the level of detail of input data is not likely to enable site specific or probabilistic assessments consistently across the country, the focus of this part of the assessment should be to ensure consistency of approach and compatibility of results between regions with differing hazards.

This should be based on extensive experience of natural hazard emergency response inspections, research and testing (where appropriate) in similar geological conditions, and review with local knowledge of network and conditions. Table 8 provides guidance on the assessment of the hazard impacts to the road. The impact would need to be assessed for the different hazards and hazard levels (such as return periods or scenarios under consideration).

Table 8 Hazard impact on road

TYPE OF IMPACT	IMPACT ON ROAD AVAILABILITY	ISSUES TO CONSIDER FOR DURATION OF IMPACT
Inundation	Potential for: ▪ scour ▪ erosion	▪ Duration of flooding or coastal inundation
Debris	▪ Quantum of debris ▪ Extent of road affected	▪ Time for clearance after flood subsides
Scour	▪ Extent of scour	▪ Time for scour repairs
Deformation / cracking	▪ Extent and magnitude of deformation ▪ Ability to access using normal vehicle or 4WD	▪ Time likely to be taken before road deformation is reinstated.
Slip onto road	▪ Quantum of slip debris ▪ Likely extent of intrusion into road ▪ Likely debris flows	▪ Time taken before slip is cleared from road. ▪ Ongoing risk of slips/instability of slope. ▪ Time for stabilisation of slip. ▪ Reinstatement of road surface.
Underslip	▪ Extent of road likely to be affected based on scale of failure ▪ Extent of road closure for safety	▪ Time taken for development of restoration design and construction.
Structure failure	▪ Extent of road likely to be affected based on scale of structure ▪ Extent of road closure for safety	▪ Time taken for development of restoration design and construction.

8. Apply resilience metrics

Purpose: Assign resilience states to road characterisation scheme.

Process: Apply the resilience states discussed in Section 4 to the categories in the road characterisation, to map the resilience of the state highway corridors. This is carried out by determining the values of availability and outage for the given hazard impacts in each category (see step 7). Assignment of resilience states is given in Table 9.

Table 9 Applying Resilience metrics

LEVEL	AVAILABILITY STATE	ISSUES TO CONSIDER
1	Full	▪ Generally the road impacts do not affect access along the road. ▪ Some care may be required during access.
2	Poor	▪ Road deformation (i.e. due to liquefaction subsidence) leads to poor access. ▪ Flooding or debris / mud from flooding makes access poor.
3	Single Lane	▪ Half the road is closed due to quantum of slip debris, considering road berm width and nature of slip materials. ▪ Underslip or structure failure / damage leads to part of the road being removed. ▪ Structural damage limits capacity and therefore reduced to single lane.
4	Difficult	▪ Extensive cracking and road deformation (i.e. due to liquefaction lateral spreading) leads to difficult access for only 4WD vehicles. ▪ Flooding or debris / mud from flooding or mud flow makes access difficult and limited to 4WD vehicles.
5	Closed	▪ Road closed due to large quantum of slip debris and / or nature of slip materials. ▪ Underslip removed more than half the road platform. ▪ Structure damage, failure or collapse restrict access and closes road. ▪ Flooding closes access on road.

Outage state is assigned considering the time taken to clear slips, repair road, and reinstate retaining walls or structures. Consideration should be given to the time likely to be taken in the context of the event, and the availability of access to the site. For example a magnitude 7.5 earthquake locally may mean that plant is initially tied up with saving lives such as in collapsed buildings.

9. Capture into GIS

Purpose: Spatial mapping of resilience states

Process: The resilience states from the road characterisation can be captured in spatial form using GIS. This would enable the resilience of the road for the key natural hazards to be displayed spatially in the regional context.

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