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EXPLORING A RISK EVALUTION TOOL FOR NEW ZEALAND STATE HIGHWAY NETWORK NATIONAL RESILIENCE PROJECT

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Abstract

The New Zealand Transport Agency is a Crown entity with primary roles including to build, maintain and operate the state highway network, and to plan and invest in an integrated transport system. The Transport Agency has formulated a highway Resilience Project and seeks to develop a framework that can be used to prioritise investment to enhance the highway resilience. This paper describes the work undertaken by GNS Science in assisting in the development of a Highway Network Resilience Prioritization Framework within which the effectiveness of various mitigation measures that aim to improve highway resilience can be measured. It included the development of a GIS based Risk Evaluation Tool (RET) that evaluates the disruption state of highway network when subjected to geological and hydrological hazard events of varying intensities. The approach used comprised of three main components: (a) Defining the geographic location of the highway and associated assets; (b) Developing various suites of hazard layers for the primary natural hazard perils to which NZ highways are exposed; and (c) For each asset or road segment, defining the relationship between damage or disruption states and the intensity of each specific hazard. The tool accepts the above inputs, overlays the hazard severity on the defined network and determines the possible damage and disruption states of each highway segment. The disruption results are presented in both spreadsheet format and also graphically with the different severities of disruption color coded on the outage map. As a proof-of-concept validation the tool has been tested on a pilot study area route in the Wellington region and has shown to deliver the desired results. It is envisaged that the highway disruption results from the RET could inform other elements of the overall Resilience Framework.

Keywords: highway network; resilience; risk evaluation; damage state; disruption state; multi-hazard

1. Introduction

The NZ Transport Agency (the Transport Agency) is a Crown entity governed by a statutory board with primary roles including to build, maintain and operate the state highway network, and to plan and invest in an integrated transport system. Over the past five years, the Infrastructure Unit of the NZ Treasury has been working to identify how New Zealand communities are exposed to potential failures of the various infrastructure upon which society depends, particularly when impacted by shock events such as earthquake or other natural perils. By enhancing the resilience of its highway network, the Transport Agency are seeking to meet Government policy expectations, its Civil Defence Emergency Management Act obligations, its Lifelines obligations (to other utilities and emergency response organisations) and societal expectations. The cornerstone of meeting such obligations is the ability to prioritise investment proposals which improve network resilience according to their effectiveness in reducing disruption to service when subjected to shock events.

Following the adoption of the State Highway Network Resilience National Programme Business Case [1], the Transport Agency commissioned a consortium led by GNS Science to formulate a Highway Network Resilience Prioritization Framework. The proposed framework consisted of the following four modules:

(a) *Risk Evaluation* module: A GIS based simulation tool to evaluate the disruption state of the various segments of the highway network when subjected to regional natural hazard events (e.g. earthquake, coastal inundation etc.);

(b) *Recovery Optimization* module: A tool that accepts the likely disruption state evaluated from above risk evaluation module, and applies recovery prioritization plans to establish the time required and pattern of a staged recovery to return to full operability;

(c) *Impact Evaluation* module: A tool that accepts the time-stamped disruption maps generated by the recovery optimization module and evaluates the implications of the various stages of network disruptions on: (i) societal recovery (e.g. emergency response, transport disruption etc.); (ii) economic recovery (e.g. regional or national economic disruption or direct loss, business continuity etc.); and (iii) risk to road users (e.g. direct casualty and fatalities etc.); and

(d) *Resilience Evaluation* module: This module accepts alternative specific resilience enhancement proposals and repeats the above process on the enhanced network, complete with the proposed resilience measures in place and evaluates the ‘improvement of each such alternative proposal in reducing the disruption and thus community impact that each or any of the hazard models may impose. This process would enable a resilience effectiveness rating to be applied to alternatives proposed and enable funding allocations to be accordingly prioritized.

The focus of this paper is on the development of the Risk Evaluation Tool undertaken by GNS Science as Phase 2 of the above Highway Network Resilience Framework.

2. The Risk Evaluation Tool

2.1. Model Development

As mentioned above, the objective of the Risk Evaluation Tool (RET) is to evaluate an immediate post-event service disruption levels to the highway network as a consequence of them being exposed to various natural hazard events. The following criteria were used to establish the basis upon which the model was developed, with the key requirements to be:

- Focused on road networks, particularly but not exclusively the State Highway network.
- Modular in form so as to enable expansion both as to the regions covered and the type / set of hazards being considered.

- Accessible to the Transport Agency staff, both from the National Office and the Regional Offices. *Note that the current version of the tool is in a web portal environment with password protected access.*
- Provided with a user interface that enables users to inspect asset data, examine the hazard layers and evaluate the Service Disruption Levels (SDL's) by event.
- Suitable for use by a basic user to operate with minimal GIS literacy but of having map-reading and highway management skills. *Note that the current version of the tool is suitable for a basic user*.
- Capable of presenting input highway asset data in an interactive map form where users will be able to gain an overall geographical appreciation of the network and to use simple screen-based selection techniques to view the various asset attributes associated with the various assets that combine to form the network.
- Capable of presenting the SDL's in the immediate aftermath of an event within an interactive map where the user can view: (a) the probable disruption pattern to the various segments of the network; and (b) the probable causative damage to the asset within the network that have resulted in those SDL's.
- Capable of downloading the resulting probable disruption results in a format that can be used for further evaluation. For example, the results were to be in a form suitable for providing as input into the proposed Social and Economic Impact Evaluation modules. *Note that the current model is capable of saving the results into a GIS shape file and also into a spreadsheet format.*

2.2. Required Datasets

Fig. 1 shows the schematic of the RET. The following three components are required to enable the tool to operate:

(a) *Highway definition*: The highway network geographically represented within a GIS layer and accompanied by a set of attributes for each road segment sufficient to enable the assignment of appropriate hazard-specific fragility functions. The GIS layer is expected to include both the highway characteristics, the various highway structures (e.g., bridge, tunnel, retaining walls, etc.) and the characteristics of the various protection works (e.g., seawall, scour protection works etc.) across the network;

(b) *Hazard modules*: A suite of hazard modules (of interest) capable of accepting the hazard intensities, geographically spread over any specified region for each member of the event sets identified for the recurrence bins of the probable events; and

(c) *Fragility functions library*: A suite of fragility functions wherein the relationship between damage or disruption states links to the intensity of each specific hazard. One such relationship is required for each asset or road segment exposed to the hazard.

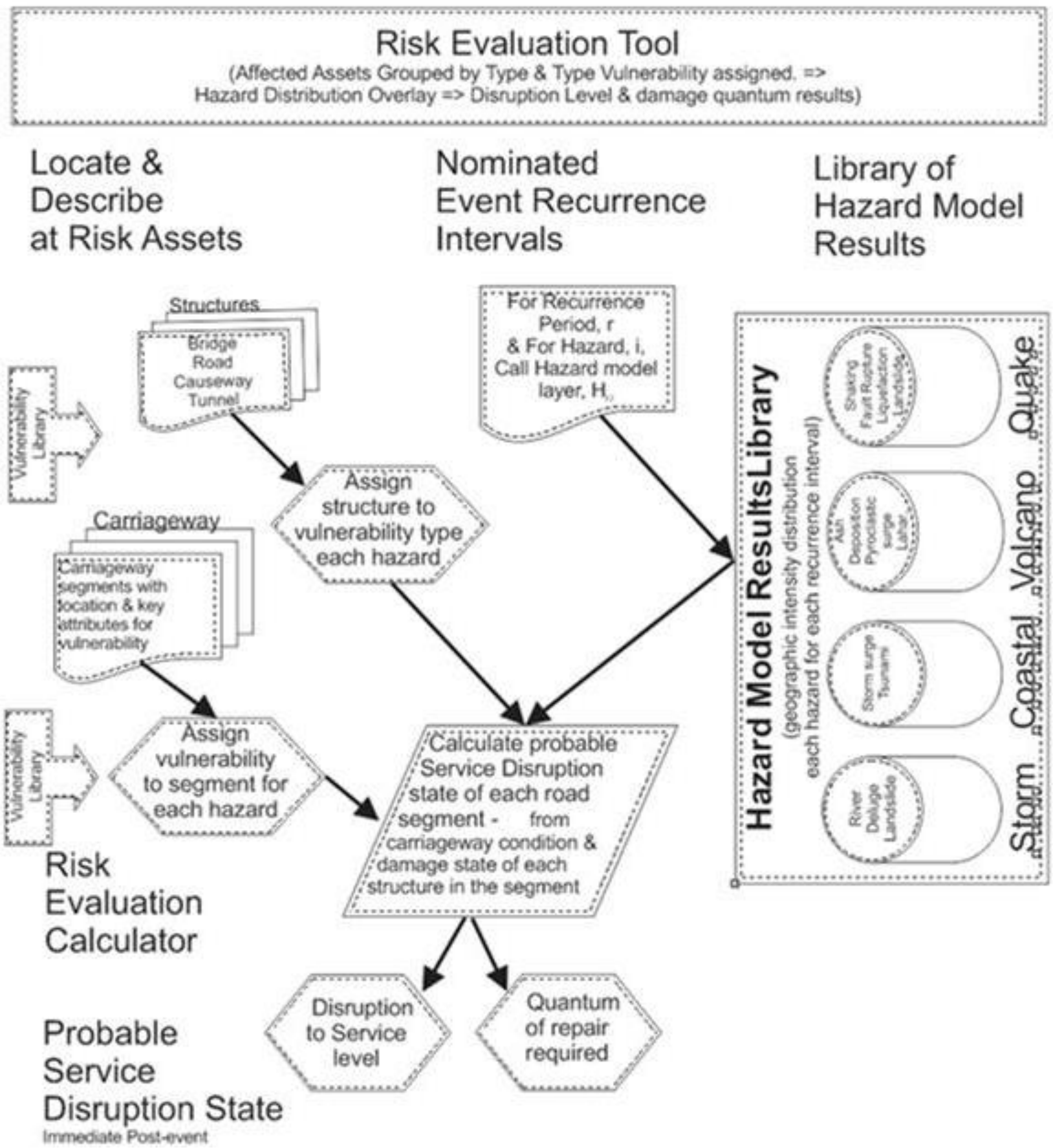


Fig. 1 – Schematic of Risk Evaluation Tool (RET)

2.3. Proof of Concept

In order to demonstrate that the proposed tool was feasible and could deliver the results that addressed the Transport Agency's requirements outlined in the above sections, it was agreed to develop the model framework and populate this with data for a pilot study area as a proof-of-concept validation. A journey of approximately 50km between Wellington city airport and Upper Hutt (a city north of Wellington) was chosen as the pilot study route. The selected route consisted of a stretch of state highway (SH) and some primary alternative local roads connecting the two cities as indicated in Fig. 2. Such a route would reasonably be expected to be subject to severe shaking (Wellington, New Zealand's capital city, being in a high seismicity region), potentially severe flooding (with the Hutt River dissecting a segment of the study area) and be subjected to coastal effects (with part of the network adjacent to Wellington Harbour).

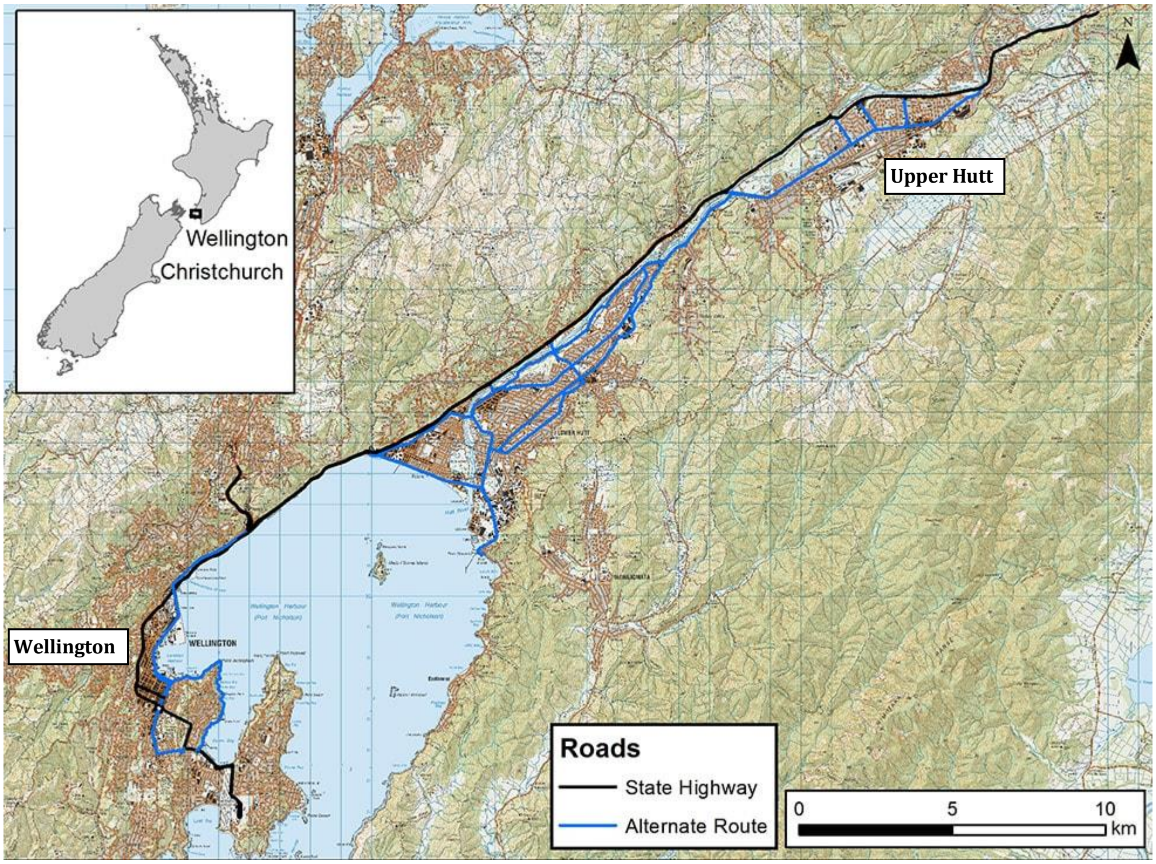


Fig. 2 – Pilot study route in Wellington region selected to test the Risk Evaluation Tool

2.4. Assets at Risk

There was no GIS layer available for the pilot study that contained all the highway information consolidated into a single GIS layer that could be readily used in the tool. Therefore, the preparation of a base GIS layer of the carriageway and the structures along the pilot study route comprised of the following:

- The geospatial representation of the road network was defined by combining the listed geospatial data: 1) the Transport Agency One Network Road Classification (ONRC) centrelines for state highways; 2) Improved NZ road centrelines; and 3) manual editing to merge the two layers. Here, the Improved NZ Road Centrelines were used in lieu of access to ONRC for non-state highways or any other suitable layer provided by the Transport Agency. The two datasets were manually edited to produce a network of spatially continuous line segments, and attributes relating to applicable hazards were applied to each line segment. The network was then divided into segments (typically start / end points of access or egress) which are used as the basis of reporting disruption, both for traffic flow across each segment and also for the assets within those segments.
- The geographic locations of the various highway structures (and their associated attributes) encountered along the route were stored in a GIS layer. A total of about 150 state highway structures were identified along the pilot study route as shown in Fig. 3. The corresponding information / attributes defining the structures (e.g. type, age, construction material, structural configuration etc.) were sourced from the Transport Agency's Bridge Descriptive System (BDS) inventory for the SH bridges and culvert structures, and an alternate data system (i.e. RAMM) for the SH tunnels and the retaining walls. For assets along the local roads, as an interim measure due to time constraints in data gathering for this proof-of-concept stage, the structures were identified using Google Maps and proxy attributes defined until further detailed information becomes available.

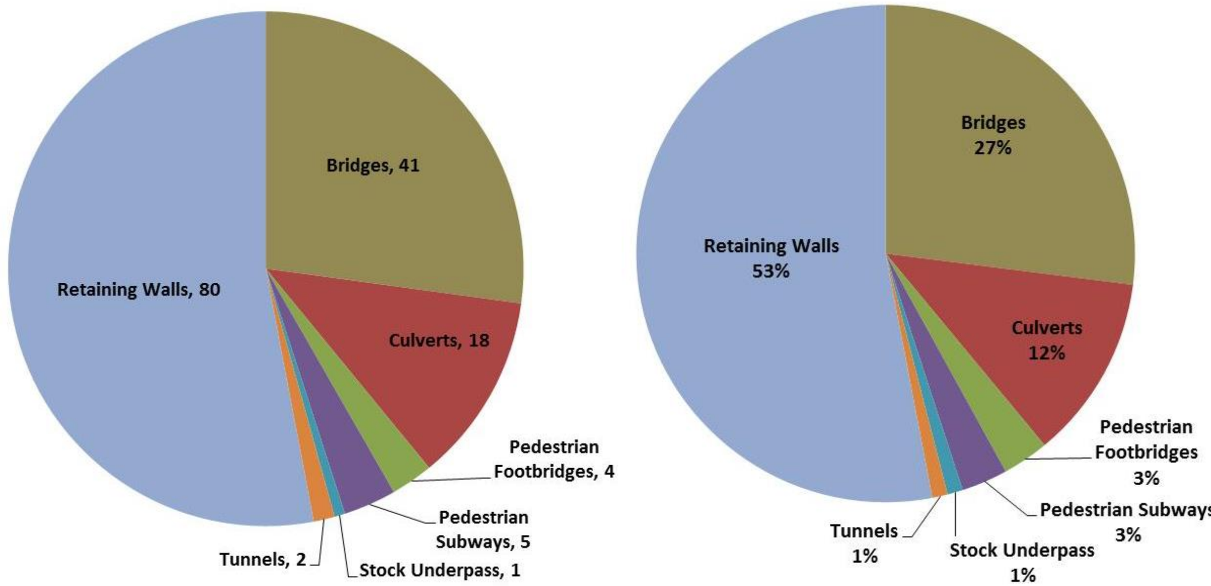


Fig. 3 – Number of State Highway structures along the pilot study route (left) and its distribution (right).

2.5. Development and Population of Hazard Event Inventory

The hazard modules / suites of hazard layers relevant to the study route were prepared by GNS Science and NIWA [2]. For example, the earthquake shaking model developed by GNS applies the regional earthquake shaking and simulates the probable disruption to road traffic due to the effects of shaking (especially on structures such as bridges, retaining walls, tunnels etc.), as well as disruption due to liquefaction and landslide induced damage caused by the shaking. The earthquake model embodied a suite of representative events for each return period of interest (i.e. 50, 100, 250, 500, 1000 and 2500 yrs) that were embedded within the tool. For this pilot, a reference location for the study area was established approximately midway along the route and geo-coded coordinates of that location were fed into the New Zealand National Seismic Hazard model (NSHM, [3]). The NSHM was queried as to the peak ground acceleration values expected for that location for each of the recurrence intervals of interest. In each case the model results were disaggregated and the characteristics of the major contributing earthquakes noted and used as the basis of selection of representative events for each recurrence interval. The motions generated at the reference location for each event were evaluated and the offset from the mean of the response distribution curve required to match the target ground motion response noted as the attenuation offset bias, with this value being used across all locations when determining the motions at each specific site for each of the recurrence intervals. Records were rejected when the attenuation offset bias was too high (i.e. > 90%) and alternative representative events retained and applied in the model.

Suites of other hazard layers prepared for the pilot study included the following: (a) Landslide distribution and severity (debris deposition and undercut/drop-out) - initiated from earthquake shaking or from storm events or from coastal inundation; (b) Liquefaction induced deformations (vertical settlement or lateral spreading) that are triggered by earthquake shaking; (c) Flood inundation layers (main rivers only); (d) Rainfall intensity tables (for riverine, local deluge and landslide triggers); and (e) Coastal inundation from storm-tides (which can be include wave setup and run-up). Note that due to pilot study limitations Tsunami or Volcanic eruption hazard types were not included in the current version of the tool. The related hazard modules are however planned to be included in the future.

2.6. Development of Fragility Functions Library

A suite of fragility functions for each hazard was developed for the highway network components (i.e. the structures and the road itself (where applicable)). For example, past and recent earthquakes have shown that bridges, tunnels and retaining walls are the common highway structures that are vulnerable to ground shaking ([4], [5], [6], [7], [8]), while significant damages to roads are also evident due to ground failure (e.g. liquefaction and surface fault rupture). For risk / loss modelling of a large numbers of assets it is helpful to group individual assets into a manageable number of defined classes with the appropriate fragility functions being assigned to all the elements. The fragility classes for the pilot study route structures were defined using the basic attributes of the structures held within the BDS and RAMM inventories. Also, in the case of bridges, some of the key attributes selected for calculating Vulnerability Index used in a NZ state highway bridges seismic screening process [9] were used. Given the short project timeframe and the availability of data, resources etc., the fragility functions were derived from various sources and using multiple approaches; for example: empirical method (e.g. for retaining walls), results from analytical methods (e.g. % New Building Standard scores [10] provided for the study route bridges), expert / engineering judgment (e.g. for tunnels) were all applied to develop the fragility functions library.

2.7. Risk Evaluation

2.7.1 Analysis Phase

The Analysis Phase typically follows the set-up and verification phase and involves the following:

1) Locate each asset within the dataset using the specified geo-referenced location (for line elements such as the retaining walls, this has been assessed as the midpoint of each line).
2) Evaluate the severity of the hazard which occurs at that specific location by referencing the hazard map with the location of the asset.
3) Evaluate the probable damage state expected for each structural asset and / or road segment by reference to the assigned fragility function for that asset or road segment. A random number is used here to allocate each structure into one of the damage states for the current scenario / analysis run. Note that uncertainty in both the specific asset performance and in the actions imposed will result in some variation in the probable condition of assets within the model and care is required when interpreting the results.
4) Evaluate the probability and extent of slope instability events expected across the region by considering the severity of triggering that occurs at each potential slide location.
5) Determine the Service Disruption Level (SDL) to the traffic flow at each structure (by reference to their specific damage state) and within each road segment (from slope instability and / or carriageway damage). Here, the SDL's relate to the ability of the road to fulfil its base function, i.e. the accommodation of unrestricted traffic flow. They do not necessarily represent the cause of the disruption nor the duration over which it is likely to return to full service. These aspects are rather addressed by reference to the damage state of the specific structures within the segment which experience damage and for which some remedial action will be required.

   Table 1 outlines the SDL's used within the pilot study. These range from SDL0 (no disruption) to SDL4 (complete closure). The intermediate levels are either partial closure or the imposition of various levels of restriction – e.g. speed restrictions, single lane flow or possible limits on vehicle weights etc.
6) Assign the SDL to each highway segment as being the most severe disruption encountered anywhere along that segment.
7) Store the resulting damage and disruption conditions into the results library.

Table 1 – Highway Service Disruption Levels

Service Disruption Level	**Disruption State**	**Percent Functional**	**Extent of damage affecting**	**Likely damage characteristics**
SDL0	None	100	None	None
SDL1	Minor	90	Fringe / shoulder	Requiring visual inspection & "patch-up" / clearing / cosmetic nature works due to any of following: (a) Debris deposition; (b) Slight settlement or minor offset of ground; (c) Minor damage to protection works such as a seawall; or (d) Minor abutment settlement, bridge expansion joint & bearing showing movement, hairline cracking and spalling to bridge elements / tunnel liner
SDL2	Moderate	75	Single lane	Requiring visual inspection & moderate amount of clearing works / repairing components (as required) due to any of the following: (a) Moderate volume of debris deposition; (b) Moderate settlement or ground offset; or (c) Cracking and spalling of bridge piers / tunnel liner exposing core, abutment backwall / wing wall cracking, anchor bolt damage, extensive cracking and spalling of shear keys, damage to restrainers, moderate offset of bearings
SDL3	Significant	50	Several lanes	Requiring detailed inspection & moderate – significant repair / stabilisation works, some rebuild / replacement may be required due to any of the following: (a) Significant volume of debris deposition, significant structural damage or collapse of short-medium high retaining walls; (b) Ripple distortion or loss of foundation support of carriageway; or (c) Bridge structural significantly compromised, tilting of substructure, approach slab rotation, joint seal failure, large spalls due to pounding, significant cracking and spalling in piers / abutment walls, large approach settlements, major ground settlement at a tunnel portal and/or extensive cracking of the tunnel liner
SDL4	Severe	< 50	Complete road closure	Requiring detailed inspection & significant repair / stabilisation works, most likely rebuild / replacement required due to any of the following: (a) Significant volume of debris / ashfall deposition; (b) Major settlement of ground; or (c) Bridge components damaged beyond repair, loss of bearing support / one or more spans dropped, foundation failure, excessive tilting and movement of abutments, culverts scoured, major cracking of tunnel liner which may include possible collapse, complete failure of a steep and / or a high retaining wall

2.7.2 RET Output

The RET is capable of presenting the analysis results (i.e. SDL's to the chosen network) within an interactive map. Also, if desired, the user can download the results both as a GIS shape file and into a spreadsheet format. This feature of the tool allows the user to quickly include the results as the start-point of other proposed modules such as Recovery Optimization tool, and Social and Economic Impact modules.

The presentation and interrogation of the results library is done by:

1) Providing a screen map display of the probable level of service disruption within each segment of the network under consideration. The highway SDL's reflect the degree by which traffic flow is inhibited as shown in Table 1 and are represented by five colour codes; where green = SDL 0, blue= SDL 1, yellow= SDL 2, orange= SDL 3 and red= SDL 4.

2) By pointing / clicking on any specific segment the disruption level evaluated and assigned to the selected segment is indicated within the onscreen results box. Additionally, the probable damage state(s) assigned to the asset(s) falling within the selected road segment is also displayed.

Fig. 4 through Fig. 12 show the screen shots of the RET at various stages of its operation. Also included in this screenshot package is an example of the representative service disruption levels (for illustration purposes) evaluated for the pilot study route under a 500 year return period earthquake.

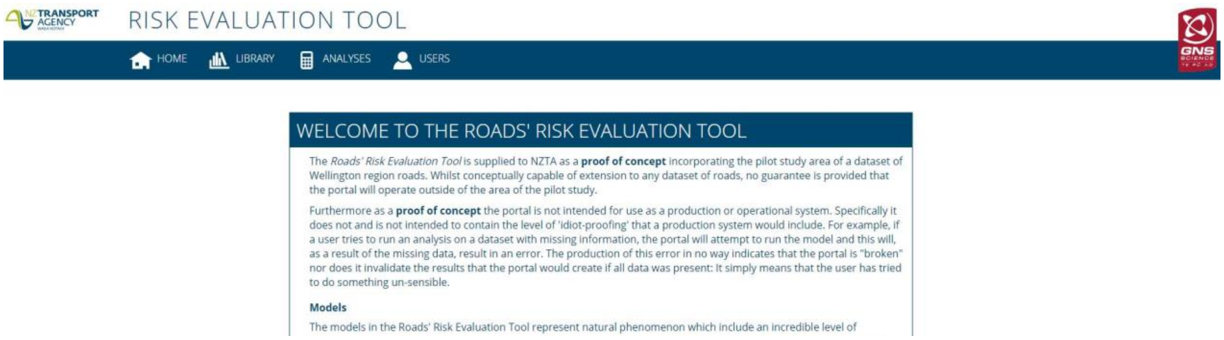


Fig. 4 – A brief descriptive text / note available to the user upon successful log-in to the portal. Log-in page to the tool is password protected.

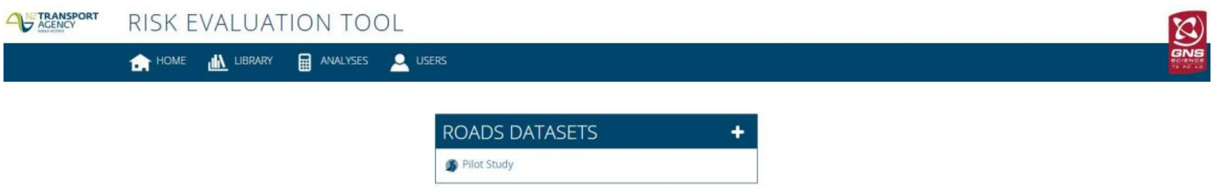


Fig. 5 – View available road datasets (e.g. Pilot Study above) and click to load into the model. Note that new road dataset files can be uploaded by drag-and-drop (under development) by clicking on the "+" button.

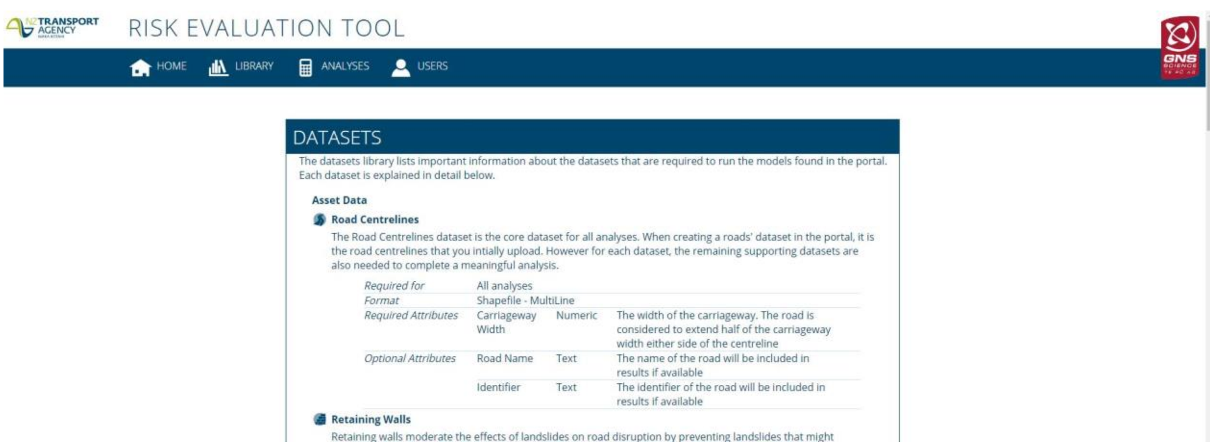


Fig. 6 – Descriptive text to the user on data set requirements to run the model (see Section 2.2).

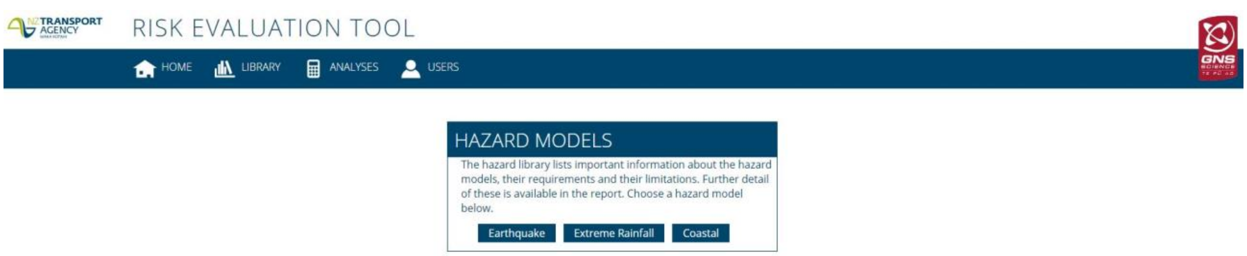


Fig. 7 – Clicking on any hazard button, description on the selected hazard model will be displayed to the user.

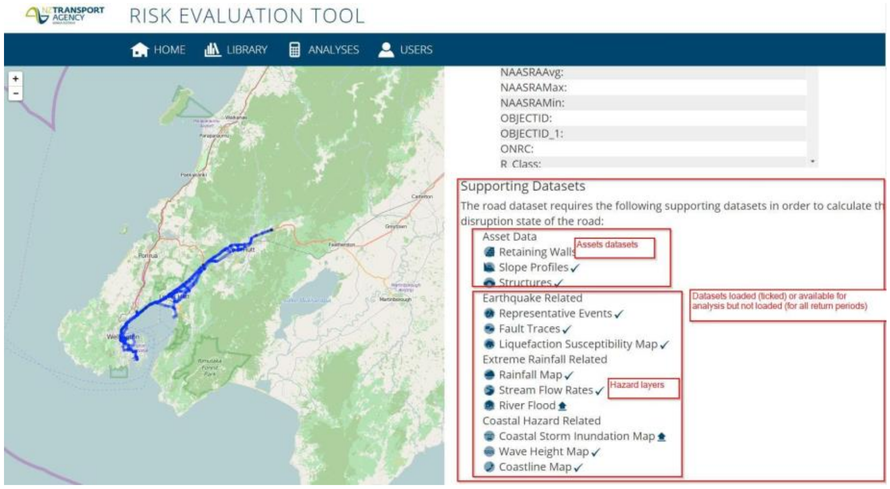


Fig. 8 – Overview of the road network to be tested and its related data set file status available for analysis.

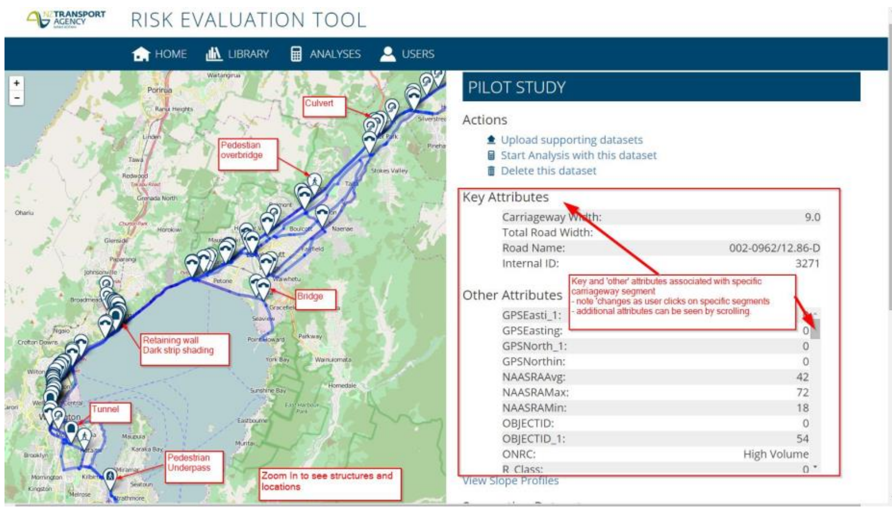


Fig. 9 – Closer view (zoomed-in) of the network to be assessed with structural locations and types identified by symbols. Clicking on any road segment on the map provides its associated carriageway attributes on the right.

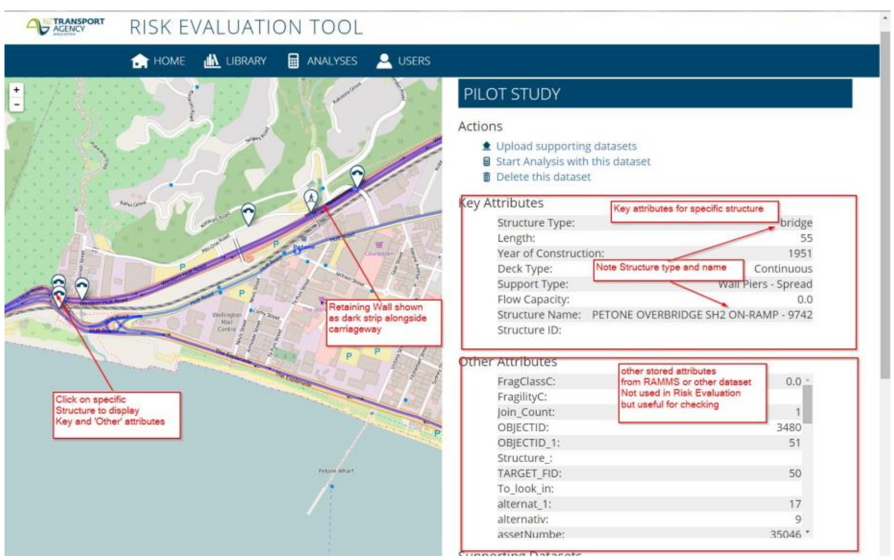
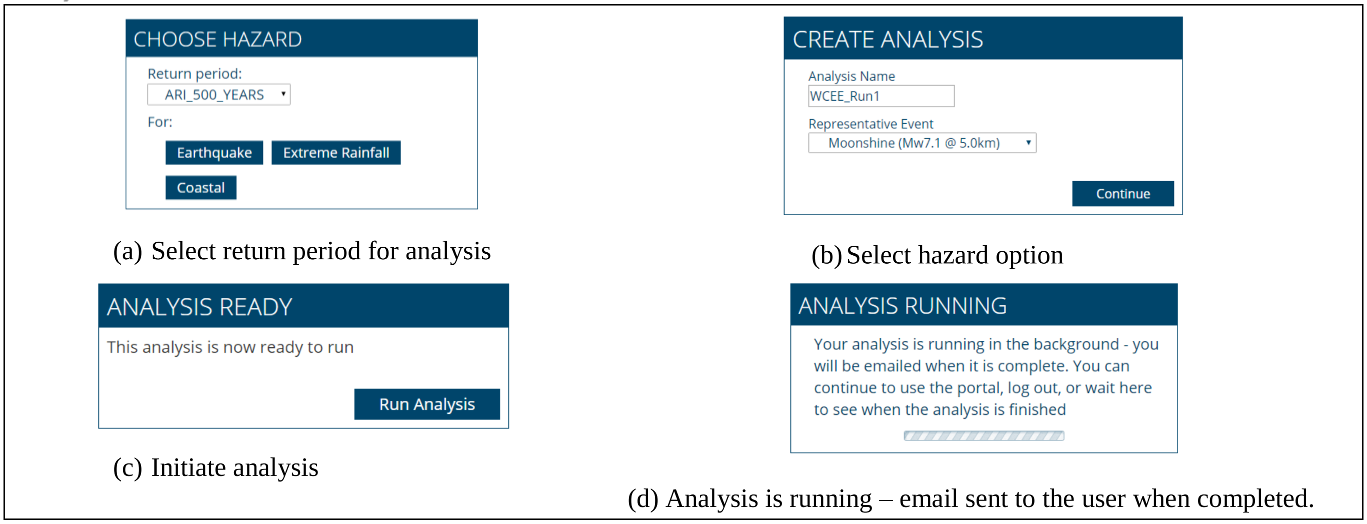


Fig. 10 – Closer view (zoomed-in): clicking on any structure on the map provides its attributes on the right.



(a) Select return period for analysis

(b) Select hazard option

(c) Initiate analysis

(d) Analysis is running – email sent to the user when completed.

Fig. 11 – The phases of analysis.

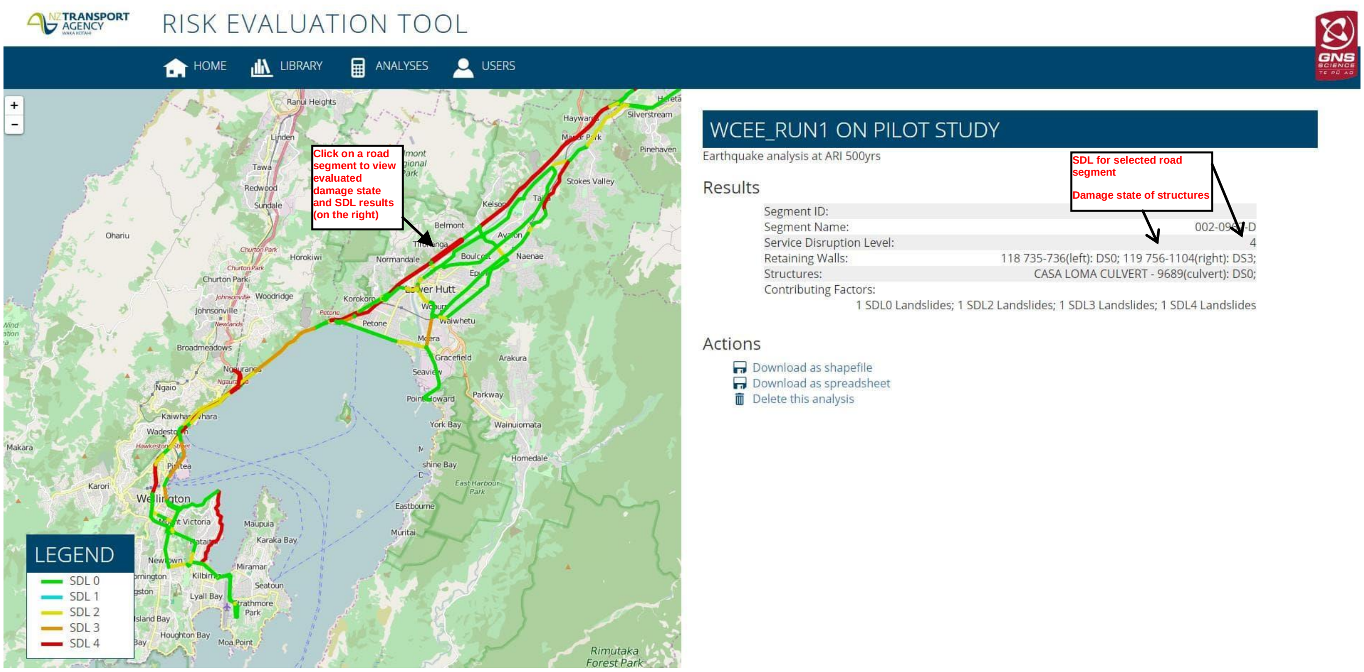


Fig. 12 – Results: screen display with damage and disruption states for the selected segment shown. Options available to export the results / delete the analysis also displayed.

3. Conclusion

This paper described the formulation of a State Highway Resilience Framework and successful creation of a highway Risk Evaluation Tool (RET) through which the risk of service disruption to any segment of the roading network can be evaluated when subjected to regional natural hazard events (e.g., earthquake, flood or coastal inundation etc.). The RET was one of the four components required within the Framework to enable the evaluation and prioritisation of alternative mitigation strategies. The Tool was formulated around specific Client requirements as being modular (with respect to hazards) and having a graphical, web-based user interface (able to both represent the assets exposed and the resulting states of disruption experienced).

The Tool needs data from three datasets, namely: (a) an exposure dataset (containing the location and characteristics of the interested roading network); (b) a library of hazard layers (which geographically portrays the severity of each hazard and for each recurrence interval of interest); and (c) a vulnerability repository (within which the damage and disruption of each asset class and / or road segment within the network is prescribed for each of the different hazards under consideration). The resulting possible levels of service disruption to each segment of the roading network are computed within the Tool and displayed through a colour coded interactive map. Additionally, the Tool provides the user with options to download the results both as a GIS shape file and into a spreadsheet format.

At the conclusion of the pilot study it was inferred that the data demanded by the model was high and that the data availability (and its reliability) can be expected to be highly variable across the country's highway network in each of the above three datasets. It was thus recognised that significant effort and time would be required to acquire or develop that data to the degree of resolution required by the model should the Tool be considered to be used for other regions. Unfortunately the timetable set for the elevation of the Tool to operational status was not compatible with the time necessary to acquire the necessary data, and therefore the Transport Agency has decided to explore less rigorous option(s) to meet its immediate goals. Further development of the Tool has been temporarily placed on hold with alternative funding streams being investigated.

4. Acknowledgements

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