Wellington landslides: The SLIDE project

S L I D E

Stability of Land In Dynamic Environments

(WELLINGTON)

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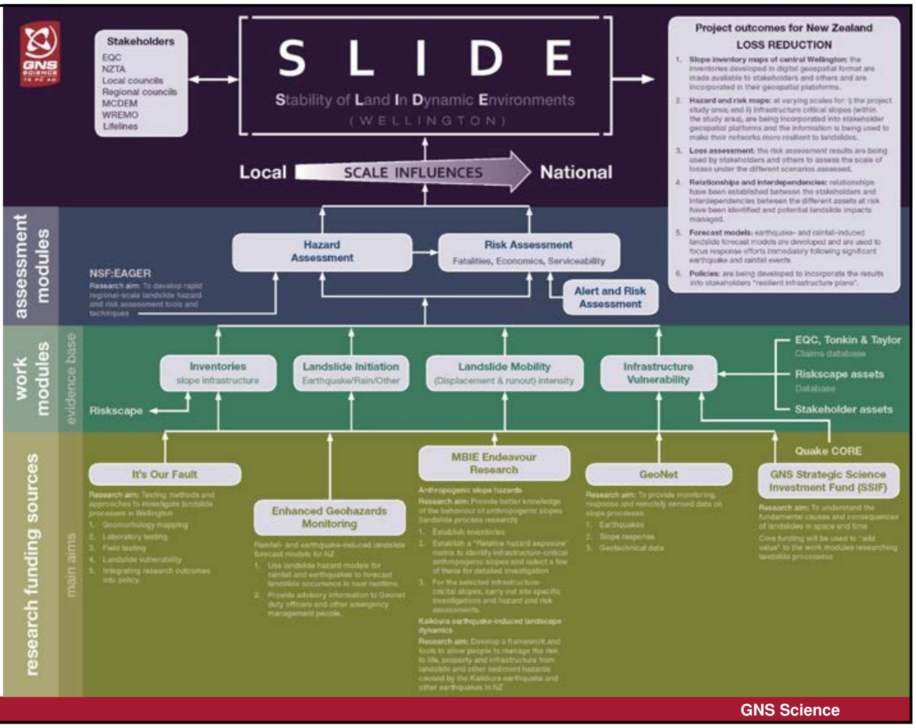
Wellington landslide work

- **Regional scale**
  - Rainfall-induced landslides (RIL)
  - EQ-induced landslides (EIL)
  - Landslide runout
  - Hazard/exposure (infrastructure)
  - Risk (life)
- **Site-specific scale**
  - Rock and Fill slope response to EQ's and rain
  - Runout of debris
- **Current research**
- **Future potential research**

Project aim: to assess the performance of natural and anthropogenic (ASH) slopes in central Wellington under earthquake shaking and significant rain events or a combination of both.

Project goal (Wellington): To improve the resilience of New Zealand's homes and infrastructure through better knowledge of the behaviour of anthropogenic and natural slopes and develop strategies for more robust remediation approaches.



Stakeholders
EQC
NZTA
Local councils
Regional councils
MCDEM
WREMO
Lifelines

SLIDE
Stability of Land In Dynamic Environments
(WELLINGTON)

Local — SCALE INFLUENCES — National

Project outcomes for New Zealand
LOSS REDUCTION

1. **Slope inventory maps of central Wellington:** the inventories developed in digital geospatial format are made available to stakeholders and others and are incorporated in their geospatial platforms.
2. **Hazard and risk maps:** at varying scales for: i) the project study area; and ii) infrastructure critical slopes (within the study area), are being incorporated into stakeholder geospatial platforms and the information is being used to make their networks more resilient to landslides.
3. **Loss assessment:** the risk assessment results are being used by stakeholders and others to assess the scale of losses under the different scenarios assessed.
4. **Relationships and interdependencies:** relationships have been established between the stakeholders and interdependencies between the different assets at risk have been identified and potential landslide impacts managed.
5. **Forecast models:** earthquake- and rainfall-induced landslide forecast models are developed and are used to focus response efforts immediately following significant earthquake and rainfall events.
6. **Policies:** are being developed to incorporate the results into stakeholders "resilient infrastructure plans".

assessment modules

Hazard Assessment

Risk Assessment
Fatalities, Economics, Serviceability

Alert and Risk Assessment

NSF:EAGER
Research aim: To develop rapid regional-scale landslide hazard and risk assessment tools and techniques

work modules — evidence base

Inventories
slope infrastructure

Landslide Initiation
Earthquake/Rain/Other

Landslide Mobility
(Displacement & runout) intensity

Infrastructure Vulnerability

Riskscape

EQC, Tonkin & Taylor
Claims database

Riskscape assets
Database

Stakeholder assets

research funding sources — main aims

It's Our Fault
Research aim: Testing methods and approaches to investigate landslide processes in Wellington
1. Geomorphology mapping
2. Laboratory testing
3. Field testing
4. Landslide vulnerability
5. Integrating research outcomes into policy.

Enhanced Geohazards Monitoring
Rainfall- and earthquake-induced landslide forecast models for NZ
1. Use landslide hazard models for rainfall and earthquakes to forecast landslide occurrence in near realtime.
2. Provide advisory information to Geonet duty officers and other emergency management people.

MBIE Endeavour Research
Anthropogenic slope hazards
Research aim: Provide better knowledge of the behaviour of anthropogenic slopes (landslide process research)
1. Establish inventories
2. Establish a "Relative hazard exposure" matrix to identify infrastructure-critical anthropogenic slopes and select a few of these for detailed investigation
3. For the selected infrastructure-critical slopes, carry out site specific investigations and hazard and risk assessments.

Kaikōura earthquake-induced landscape dynamics
Research aim: Develop a framework and tools to allow people to manage the risk to life, property and infrastructure from landslide and other sediment hazards caused by the Kaikōura earthquake and other earthquakes in NZ

GeoNet
Research aim: To provide monitoring, response and remotely sensed data on slope processes
1. Earthquakes
2. Slope response
3. Geotechnical data

Quake CORE

GNS Strategic Science Investment Fund (SSIF)
Research aim: To understand the fundamental causes and consequences of landslides in space and time
Core funding will be used to "add value" to the work modules researching landslide processes

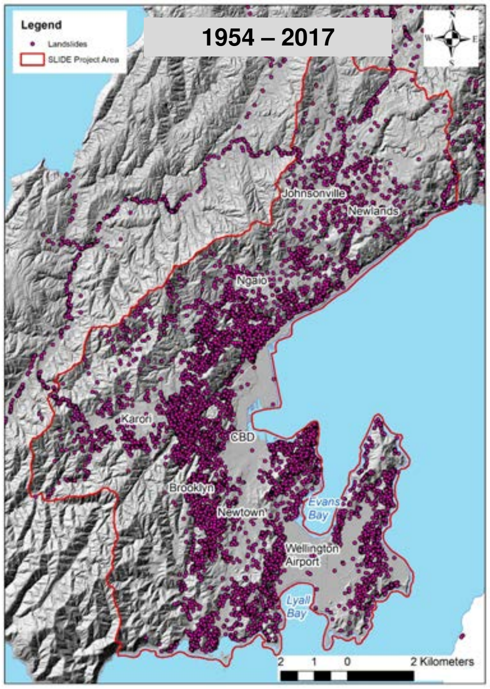
Landslides in Wellington: RIL

In the last six years:

2013 Priscilla Crescent

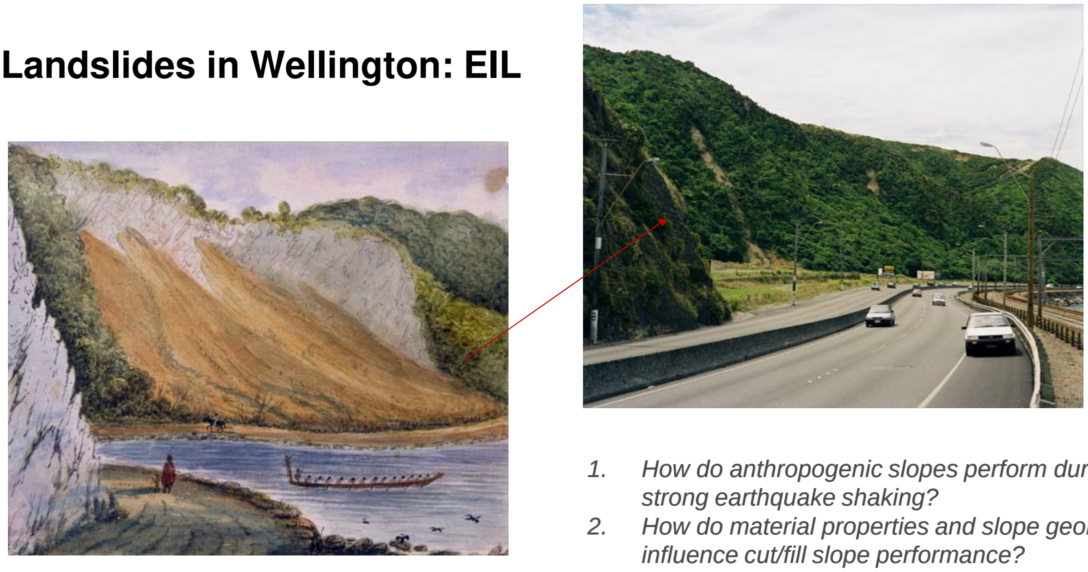
2017 Halifax Street

2017 Ngauranga Gorge



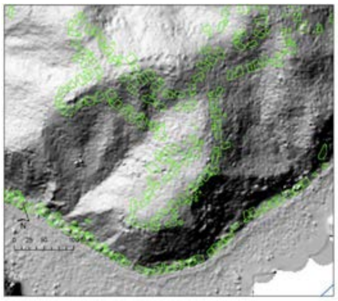
Regional-scale landslide models

Landslides in Wellington: EIL



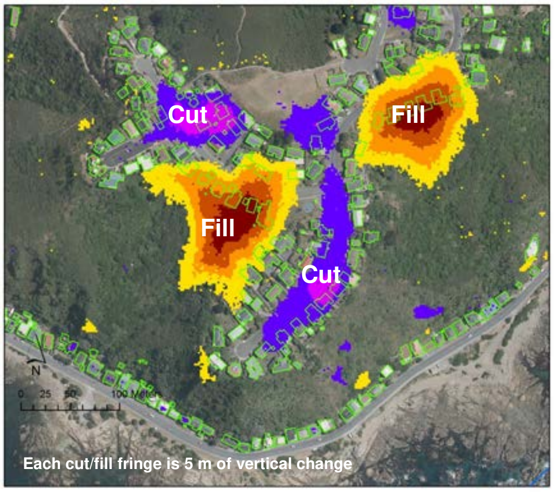
Gold's Landslide, 1855 Wairarapa EQ

1. *How do anthropogenic slopes perform during strong earthquake shaking?*
2. *How do material properties and slope geometry influence cut/fill slope performance?*
3. *How vulnerable are infrastructure to the types of landslide hazards affecting Wellington?*

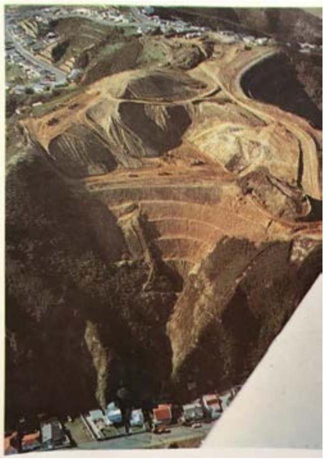


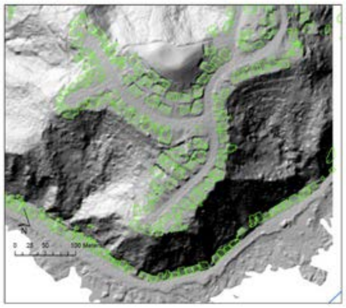
1938 surface model

Where are the modified slopes?



Each cut/fill fringe is 5 m of vertical change





2013 surface model

Surface differencing (2013 – 1938)
1600 identified fill bodies

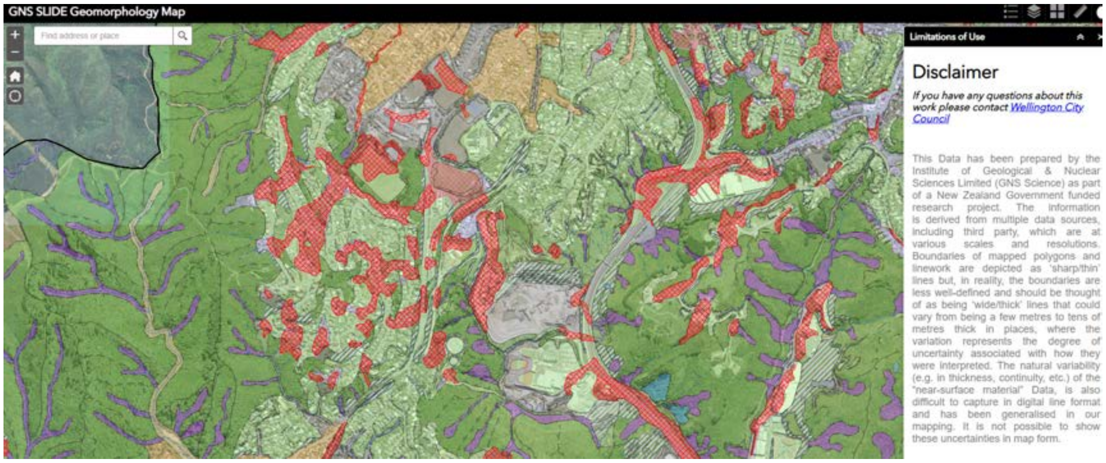
Slope inventories: Geomorphic mapping

Three layers developed
- Slope morphology
- Interpreted materials at/near surface
- Their genesis

Feeds into the hazard models

Geomorphic maps are live on WCC website!

- https://wcc.maps.arcgis.com/apps/webappviewer/index.html?id=b7b5ad358c66476087fd3163f693b4ff



Disclaimer

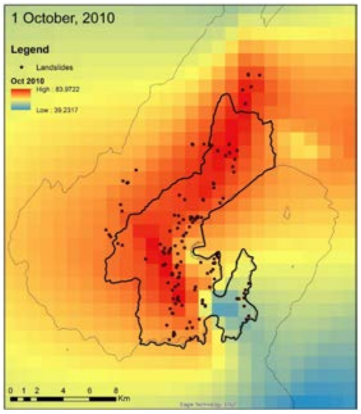
If you have any questions about this work please contact Wellington City Council

This Data has been prepared by the Institute of Geological & Nuclear Sciences Limited (GNS Science) as part of a New Zealand Government funded research project. The information is derived from multiple data sources, including third party, which are at various scales and resolutions. Boundaries of mapped polygons and linework are depicted as 'sharp/thin' lines but, in reality, the boundaries are less well-defined and should be thought of as being 'wide/thick' lines that could vary from being a few metres to tens of metres thick in places, where the variation represents the degree of uncertainty associated with how they were interpreted. The natural variability (e.g. in thickness, continuity, etc.) of the "near-surface material" Data, is also difficult to capture in digital line format and has been generalised in our mapping. It is not possible to show these uncertainties in map form.

Wellington rainfall-induced landslides modelling

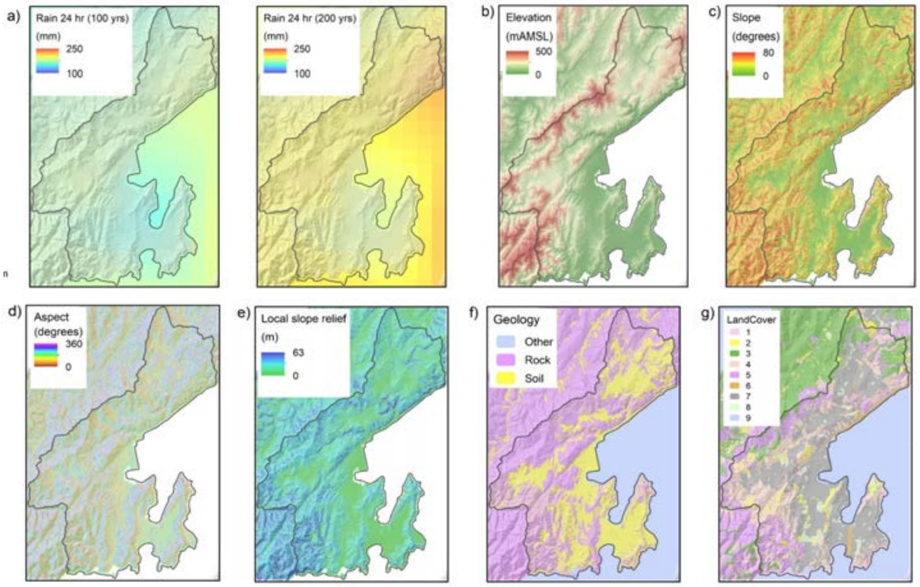
- **Landslide database:**
  - 16,175 landslide points in the dataset
  - Volumes for 7,964 landslides
  - Locations for rainfall induced landslides spanning 1954 – 2017
- **Landslide distributions for worst 20 storms**
  - Used 11 storms for modelling (~12,000 landslides)
  - Constructed rainfall grids for each storm based on 24hr max rainfall
  - Constructed Soil Moisture Indices
  - Other variables tested in the models

Landslide locations



Storm rainfall

LR, BBN and AI models used to investigate landslide controls



a) Rainfall (HIRDS: RP 50, 100 and 200 yrs) and SMD wet and dry
b) Elevation
c) Slope angle
d) Aspect
e) Local slope relief (sharp breaks in slope)
f) Geology (materials)
g) Land cover (LCD)
h) Slope curvature

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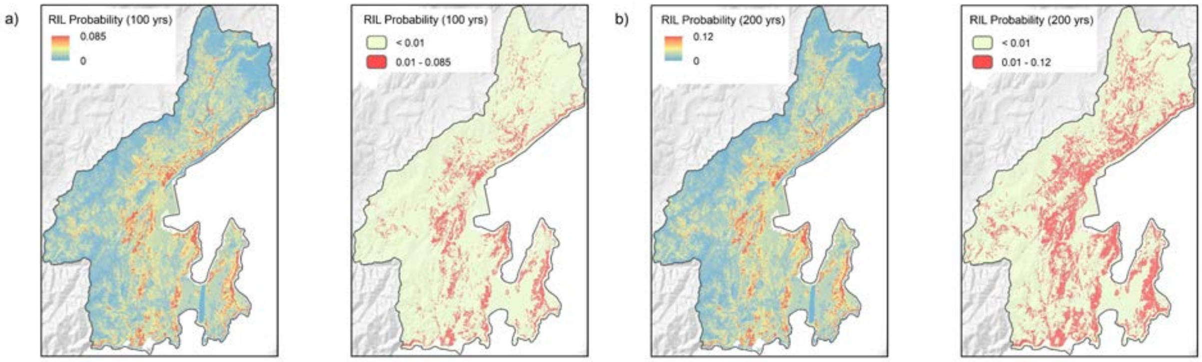
Rainfall-induced landslide (RIL) model: Probability

- **Probability of a landslide occurring at a given location if subjected to 24 hour rain amounts (100 and 200 yr return periods)**



ARI 100 yrs = 150 mm/24 hrs

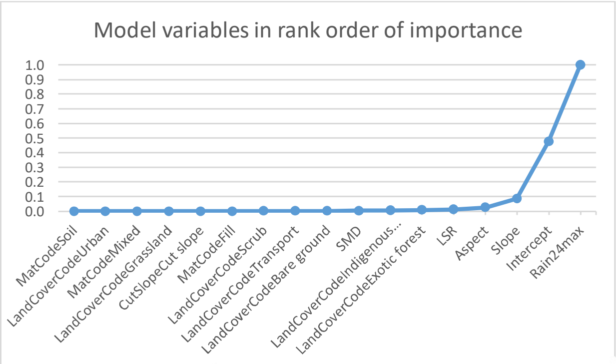
ARI 200 yrs = 200 mm/24 hrs

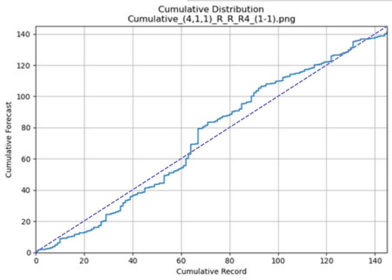
Note: RIL probability is much less than the EIL probability for a Wellington Fault EQ

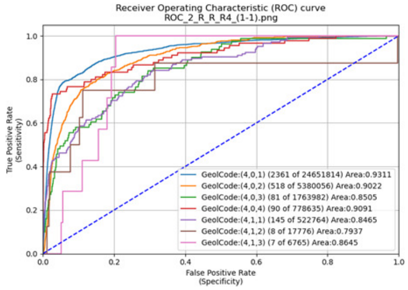
GNS Science

Statistical performance of models (LR and AI)

- ROC curves based on training datasets sampled from ALL storms
- Use model trained on training data to forecast the landslides from each individual storm
- For each storm show model versus actual, N landslide plots





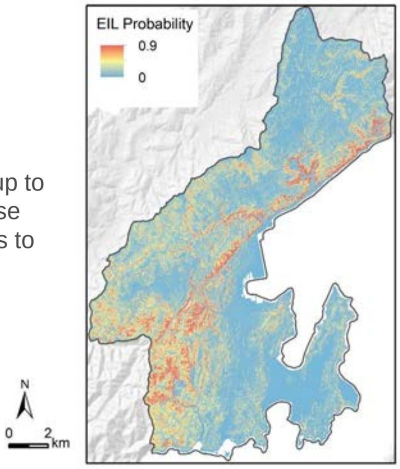


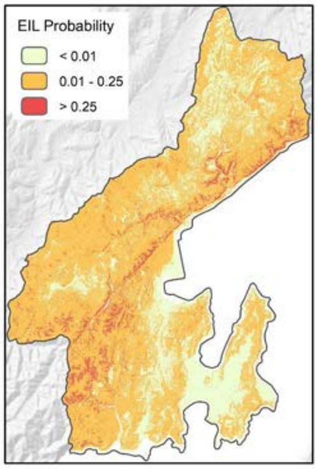
Earthquake-induced landslide (EIL) model

- Probability of landslide occurring at a given location if subjected to a given PGA
- Model is V2.0 EIL forecast tool (presented by Massey et al., 2018; 2020; 2021, based on multiple EIL datasets)

Wellington example adopting a Wellington Fault M7.8 EQ.

The model is also setup to be event driven and use instrument PGA/PGV's to generate landslide probability advisory information (maps) minutes after being triggered.

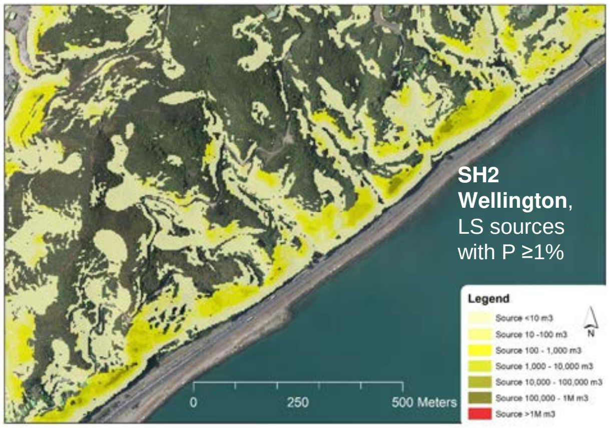




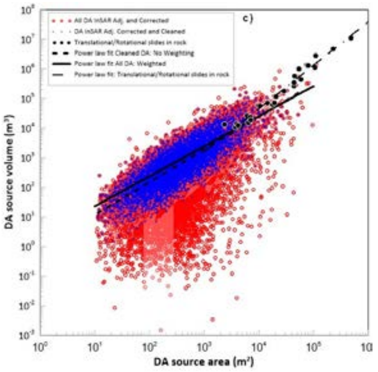
Only large slopes can generate large landslides

- Where do large slopes capable of generating large landslides occur?
- These can then be ranked based on their estimated probability of failure

Landslides in greywacke generated by the Kaikoura EQ

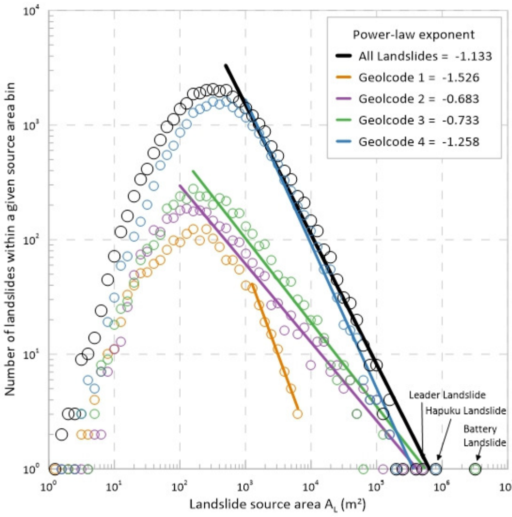


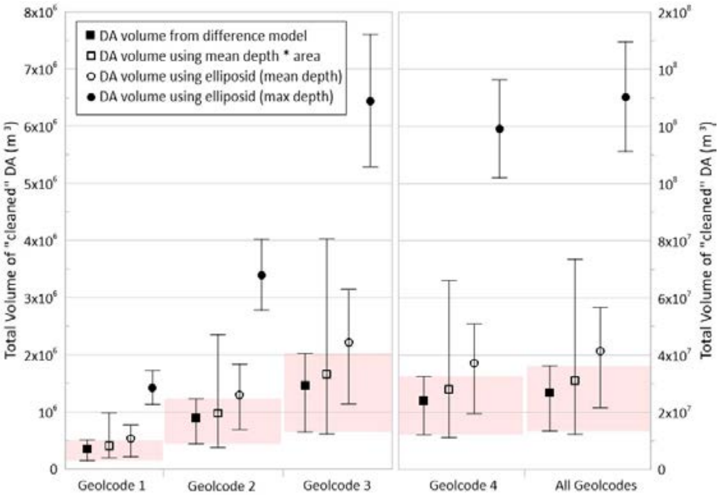
SH2 Wellington, LS sources with P ≥1%



Landslide area to volume scaling relationships and local slope relief (LSR) used to identify the largest landslide (volume) a slope may generate (Massey et al., 2020)

Estimating the total EQ volume contributed by different types of landslide in different materials





Soil

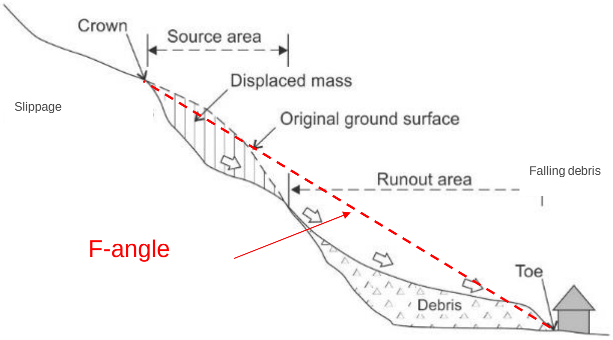
Siltstone and sandstone

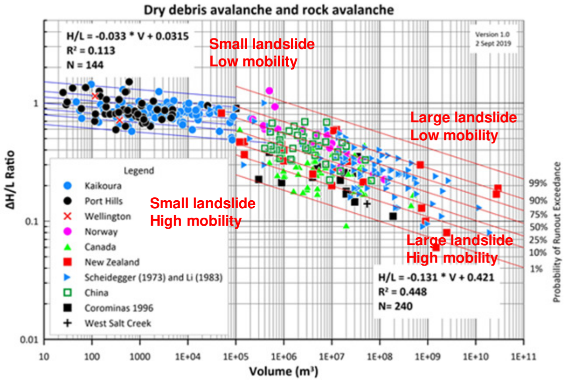
Limestone, siltstone and sandstone

Greywacke

Jones et al., (2021)

How far will the debris travel downslope? (Landslide Impact Area)



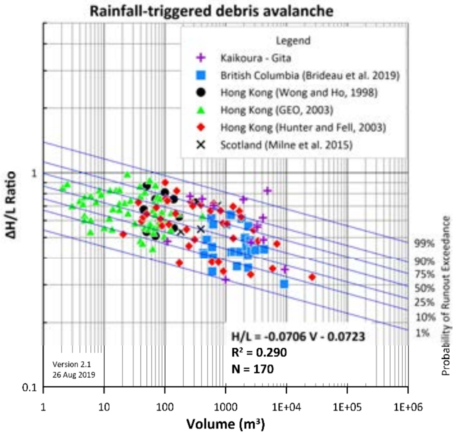


- Empirical models can be run quickly over large areas e.g., the Fahrboeschung model (F-angle)

Regional-scale: How far will the debris travel downslope?

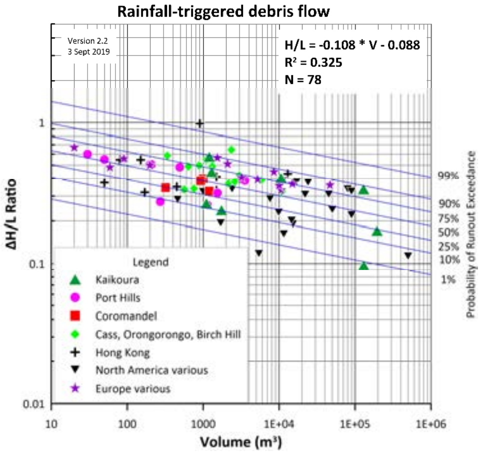
- Earthquake-induced versus rainfall-induced landslide runout
- Runout (F-angles) vary with volume, upstream catchment area, source material and the type of failure

Left, Kaikoura EQ-induced debris avalanche; Right, rainfall-induced reactivation of debris, and debris flow



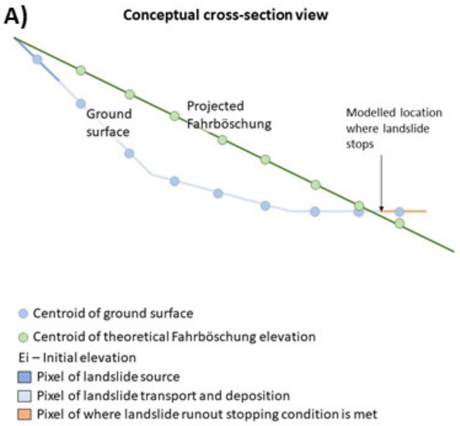
Channelled versus open slope debris

- Debris can channelized along drainage lines
- Channelised debris can travel further
- Both channelized and open slope models can be easily run over large areas
- Runout distance depends on confinement, source volume, and water content



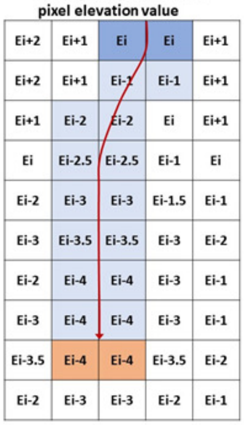
Empirical debris runout model

- Conceptual representation of the landslide runout models as implemented in GIS
  - Channelised: source elevations projected cell by cell only downhill along the steepest path and stops at the given F-angle
  - Open slope: Uses visibility tool in GIS to identify which areas can be seen from a given cell adopting the given F-angle values



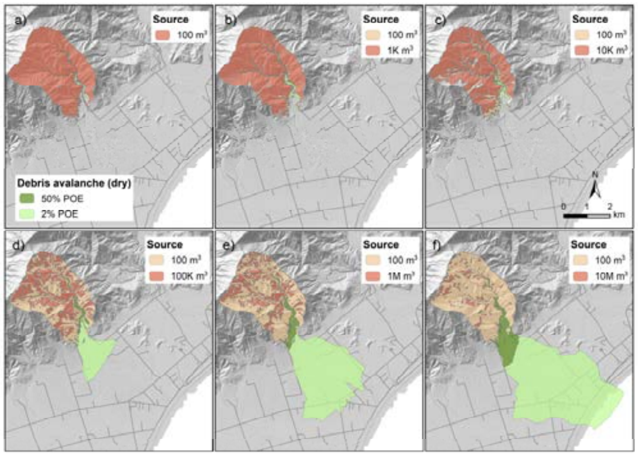
● Centroid of ground surface
● Centroid of theoretical Fahrböschung elevation
Ei – Initial elevation
▨ Pixel of landslide source
☐ Pixel of landslide transport and deposition
▨ Pixel of where landslide runout stopping condition is met

Conceptual plan view of pixel elevation value



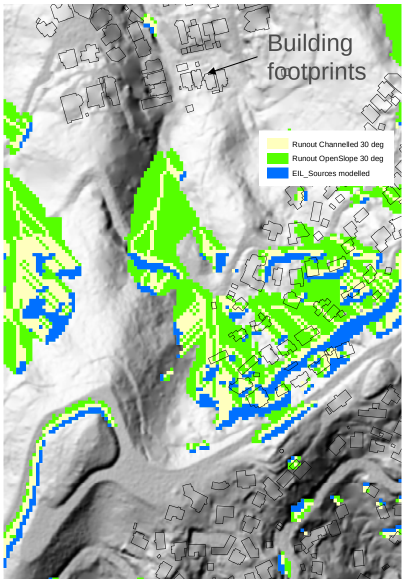
Ei+2	Ei+1	Ei	Ei	Ei+1
Ei+2	Ei+1	Ei-1	Ei-1	Ei+1
Ei+1	Ei-2	Ei-2	Ei	Ei+1
Ei	Ei-2.5	Ei-2.5	Ei-1	Ei
Ei-2	Ei-3	Ei-3	Ei-1.5	Ei-1
Ei-3	Ei-3.5	Ei-3.5	Ei-3	Ei-2
Ei-2	Ei-4	Ei-4	Ei-3	Ei-1
Ei-3	Ei-4	Ei-4	Ei-3	Ei-1
Ei-3.5	Ei-4	Ei-4	Ei-3.5	Ei-2
Ei-2	Ei-3	Ei-3	Ei-2	Ei-1

Empirical debris runout model

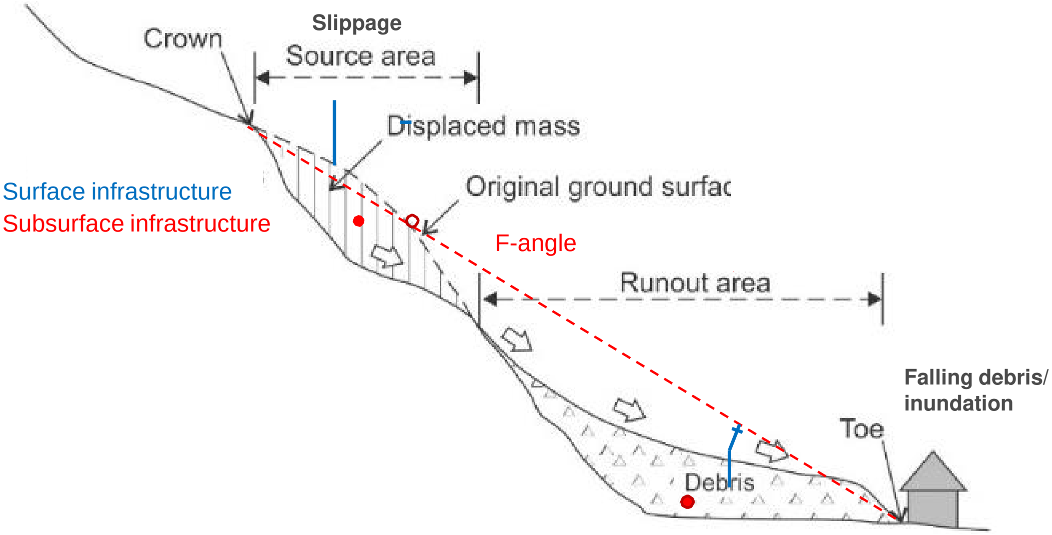


Earthquake-induced landslide runout probability of exceedance (50% and 2.3%) Fahrböschung extents for given volume classes of open slope dry rock and debris avalanches for an example watershed.

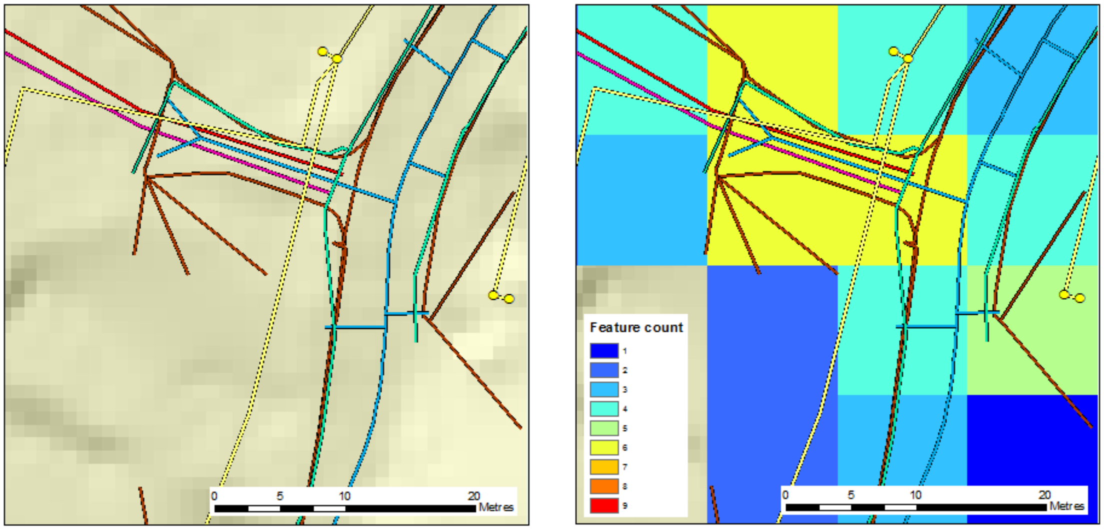
Channelised and open slope model differences



Hazard exposure matrix: Surface and subsurface infrastructure

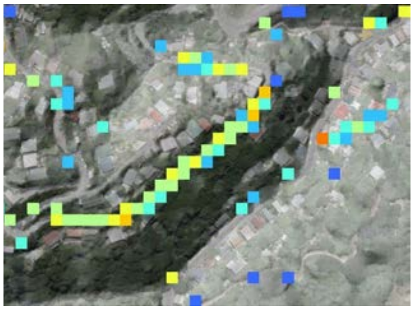


Combining landslide hazards with Infrastructure: Hazard exposure matrix

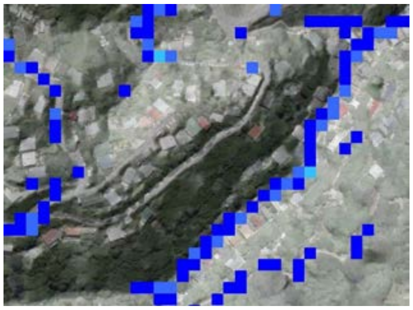


Heron et al. (2020)

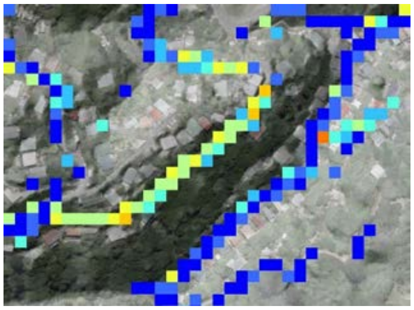
Hazard exposure matrix: Intersection of landslides and infrastructure



Intersection of source area landslide and infrastructure

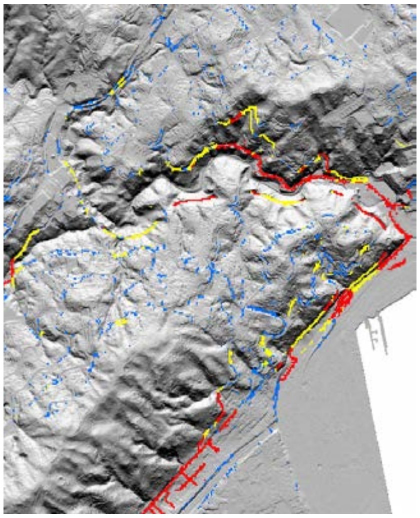


Intersection of landslide deposition area and infrastructure

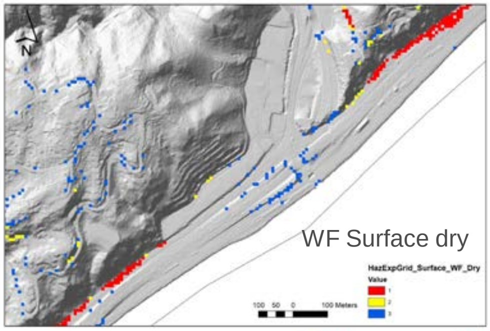


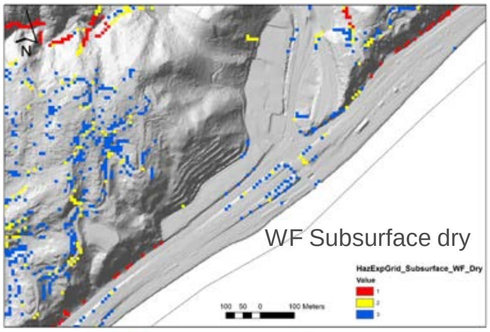
Intersection of landslide source and deposition areas and infrastructure

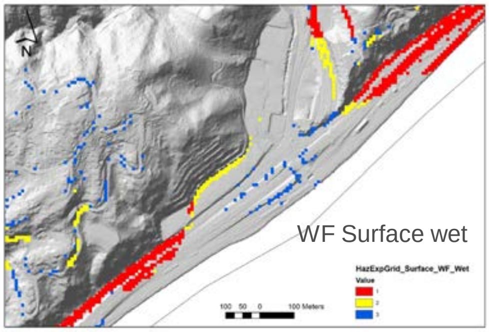
Hazard exposure matrix: intersection of landslides and infrastructure

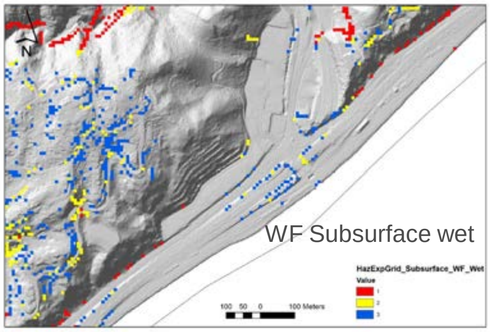


Exposure class	Hazard class (low to high probability)				
	P <0.01	P >0.01 to 0.1%	P >0.1 to 1%	P >1 to 10%	P >10%
1	3	3	2	2	1
2	3	2	2	1	1
3	2	2	1	1	1
4	2	1	1	1	1



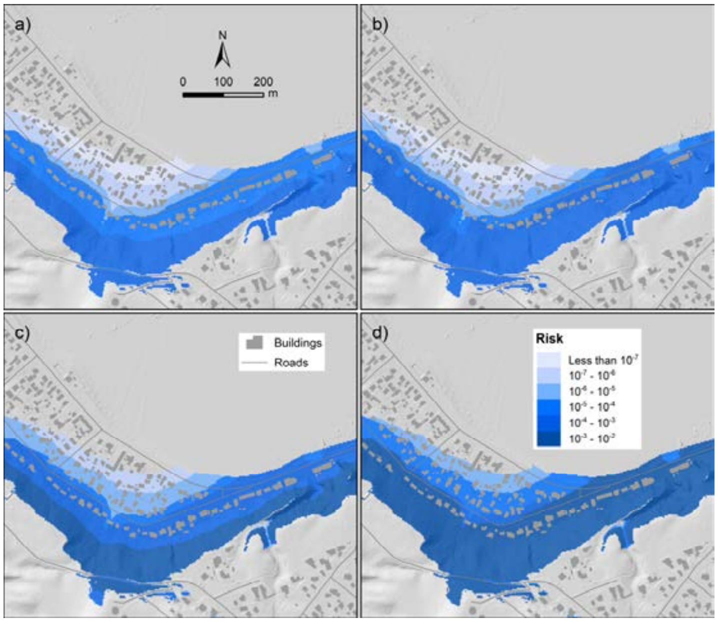






Risk: AIFR

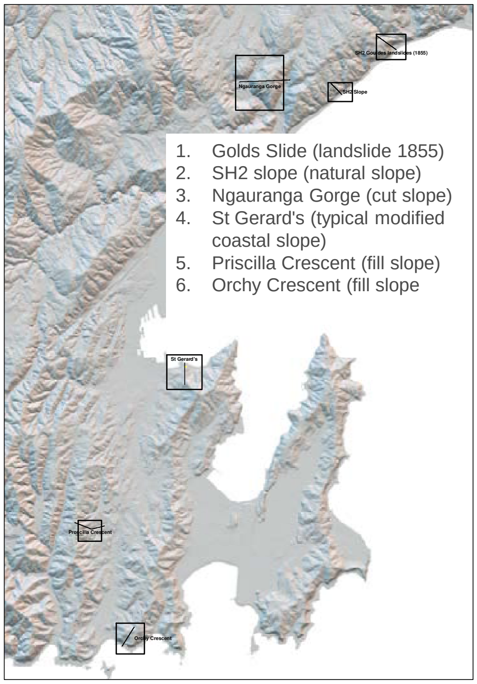
- Risk model results for ‘mean’ scenarios 1 (a) to 4 (d), adopting different values for the variables used in the risk model. The figure shows the impact on the risk estimates based on the different values selected for the variables used in the model. Risk scenario 1 (a) is the least conservative and risk scenario 4 (d) is the most conservative.



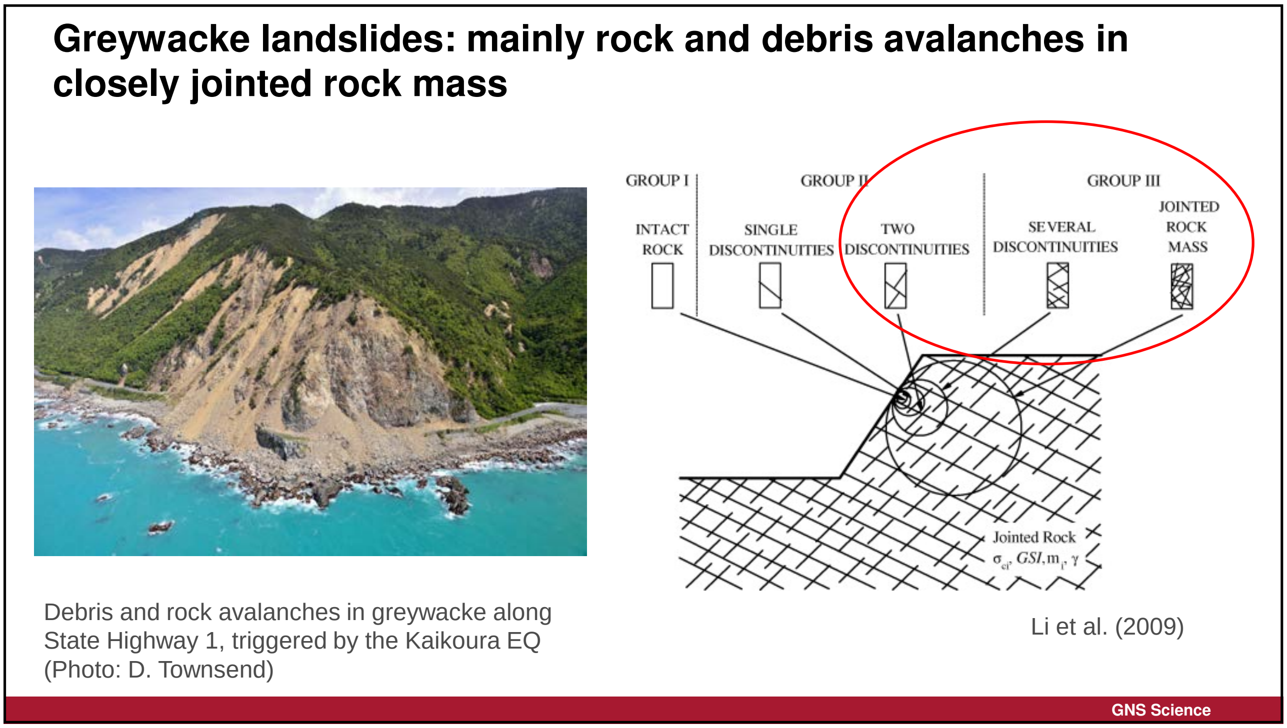
Massey et al. (2021)

SLIDE: Site-specific assessments

- Aim: to assess at the site-scale, the likely performance of the slope in future significant rain and EQ events (validate regional-scale models)
- Six sites chosen, based on a combination of:
  - Impact should they fail
  - Characteristic of the slopes in Wellington
  - Natural versus anthropogenic
  - Efficacy (logistics etc.,)
  - Co-funding (NZTA thank you!)
- Each site assessment comprises:
  - Field mapping (and geophysics)
  - Ground investigation (drilling and geophysics
  - Lab testing (Dr Jon Carey)
  - Numerical stability and runout modelling
  - Hazard and risk assessment



1. Golds Slide (landslide 1855)
2. SH2 slope (natural slope)
3. Ngauranga Gorge (cut slope)
4. St Gerard's (typical modified coastal slope)
5. Priscilla Crescent (fill slope)
6. Orchy Crescent (fill slope

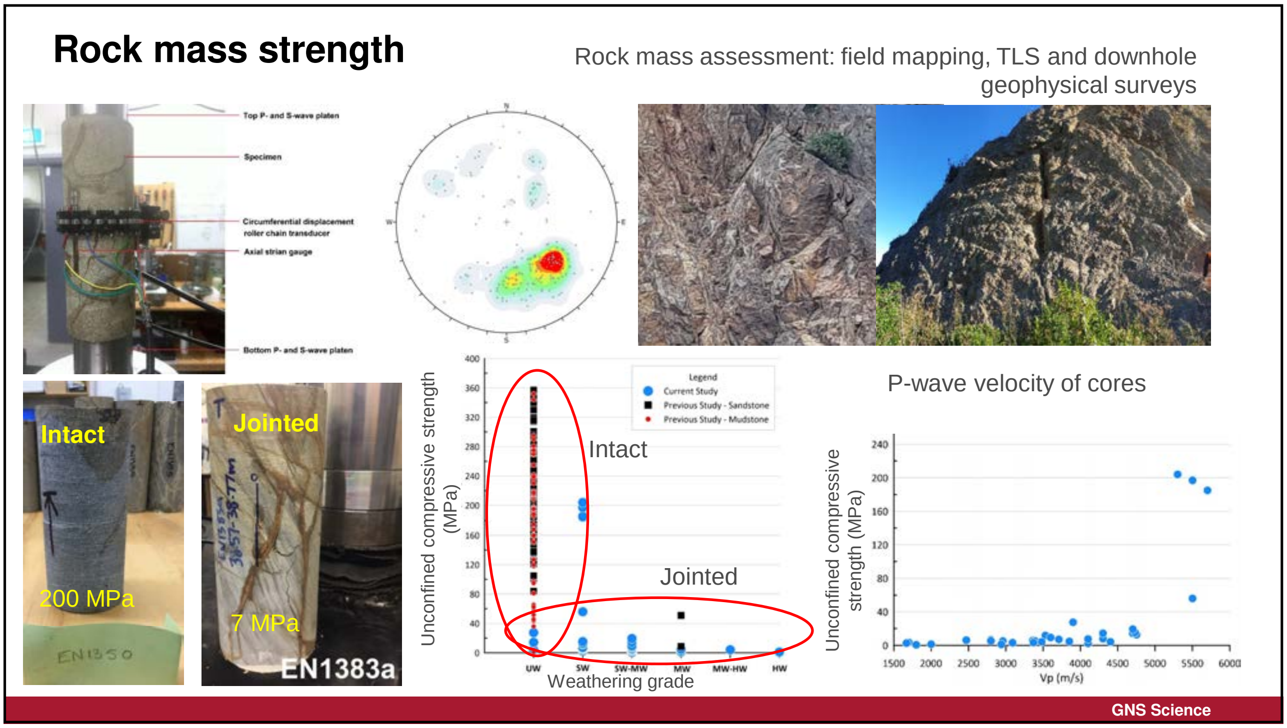


Greywacke landslides: mainly rock and debris avalanches in closely jointed rock mass

Debris and rock avalanches in greywacke along State Highway 1, triggered by the Kaikoura EQ (Photo: D. Townsend)

Li et al. (2009)

GNS Science



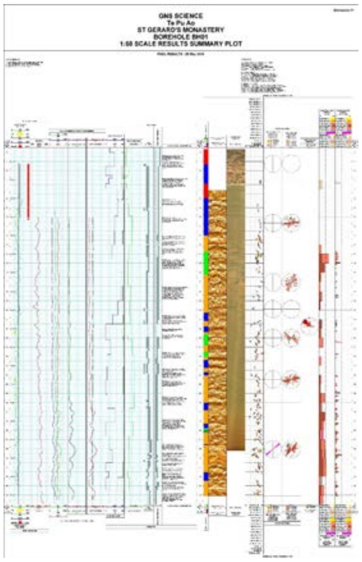
Rock mass strength

Rock mass assessment: field mapping, TLS and downhole geophysical surveys

P-wave velocity of cores

GNS Science

Down-hole imaging and data processing

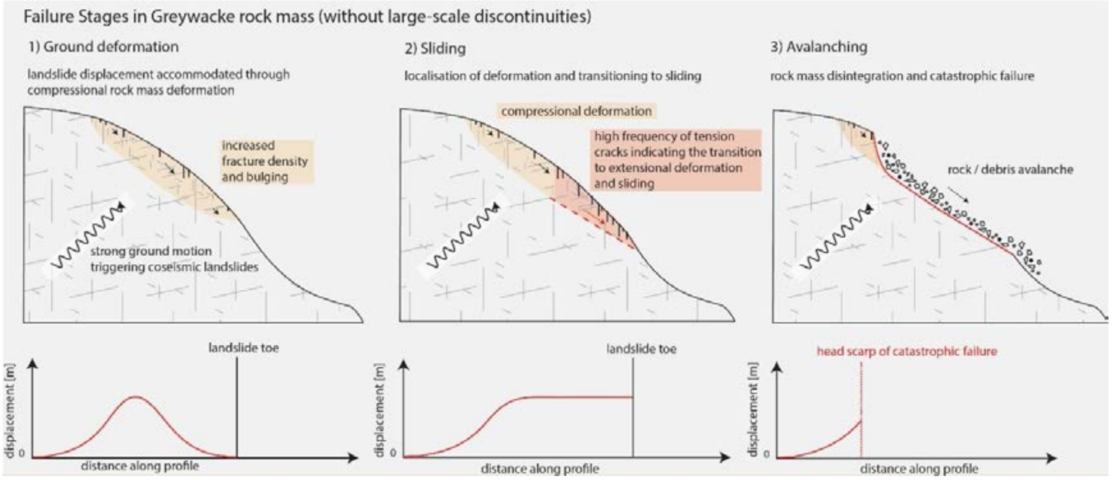


GNS SCIENCE
Te Pu Ao
ST GERARD'S MONASTERY
BOREHOLE BH01
1:50 SCALE RESULTS SUMMARY PLOT

- Full waveform sonic (P- and S-wave, shear and bulk modulus)
- Gamma
- Density
- Core data and descriptions (RQD lithology etc.)
- Downhole camera and Borehole televiewer (fractures, bedding etc, and their dip/direction and density)

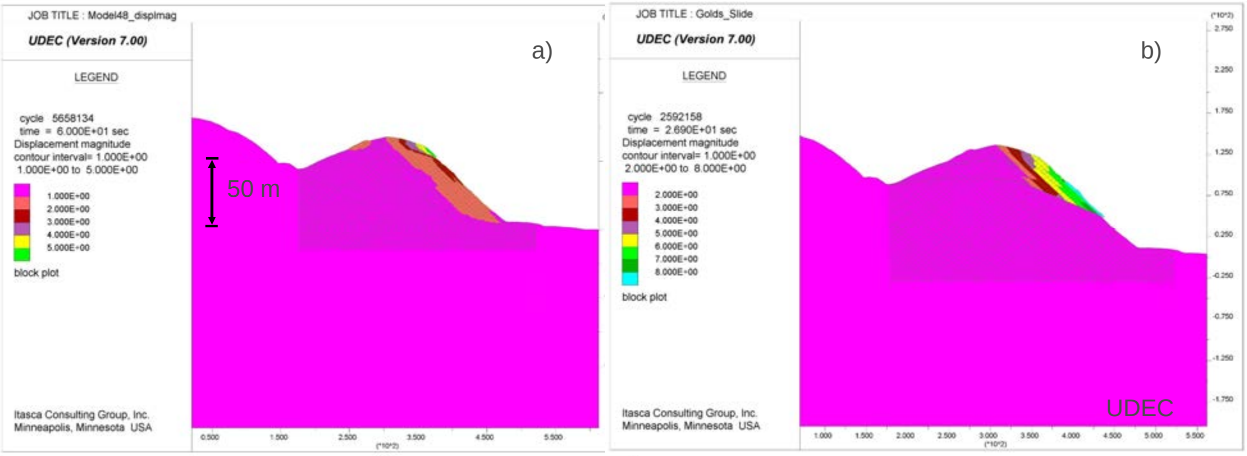
Griffin et al. (2019)

EGM: Conceptual models – EQ-induced greywacke landslides



Singeisen (2021)

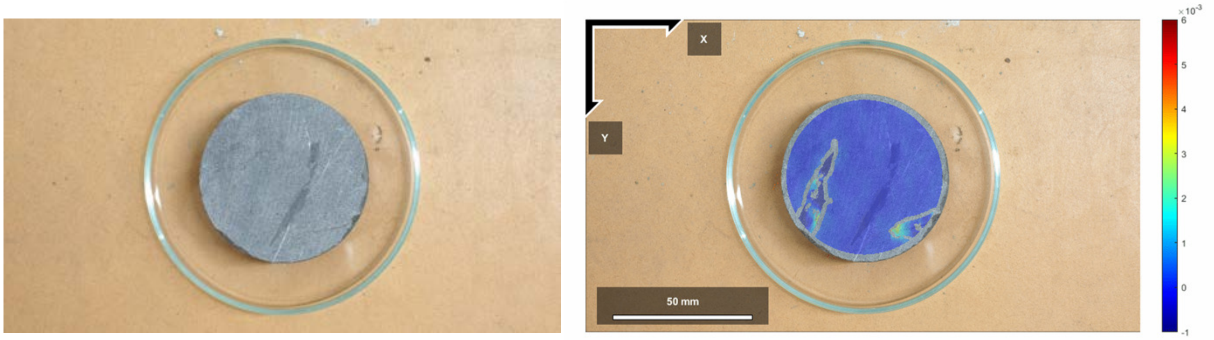
Stress-deformation analysis: How much strain is needed to transition the rock mass from sliding to avalanching?



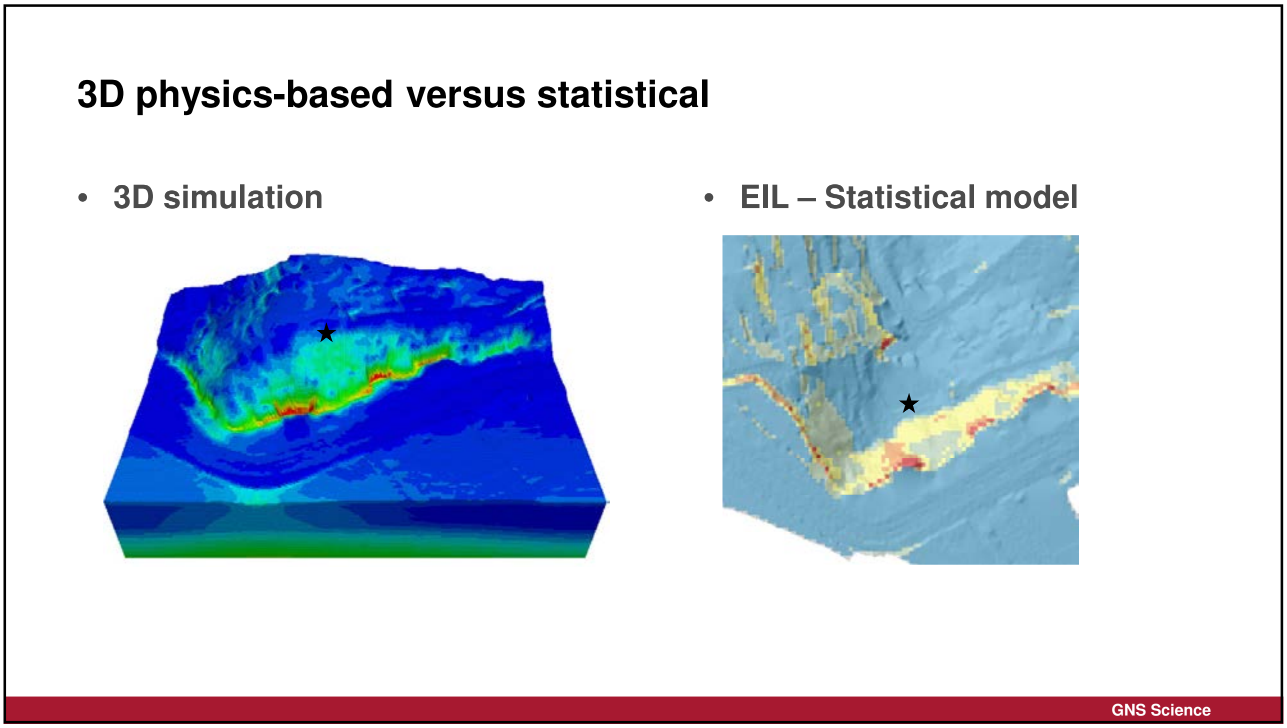
- **Investigating the role of geology and jointing on seismic response of greywacke slopes**
  a) A) Jointed model (strength-strain reduction) = larger and more localized (shallow) permanent displacements
  b) B) Pre-existing large persistent defect = large and deeper-seated permanent displacements

Not just EQ’s: Strains along defects in greywacke from wetting (post earthquake failures)

- **EQ cracks the slope, making the rock mass more susceptible in post-EQ rain and EQ events.**
- **Strains are large enough to cause permanent displacement**

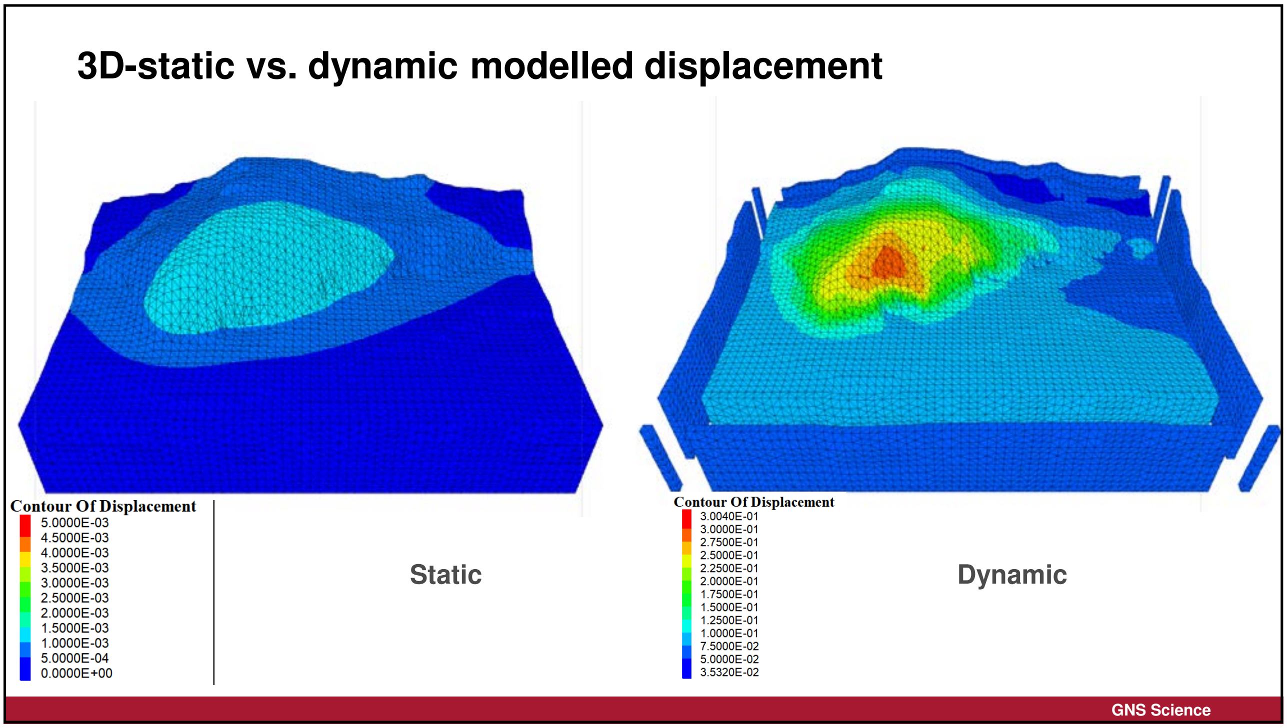


Leith (2021)



3D physics-based versus statistical

- 3D simulation
- EIL – Statistical model

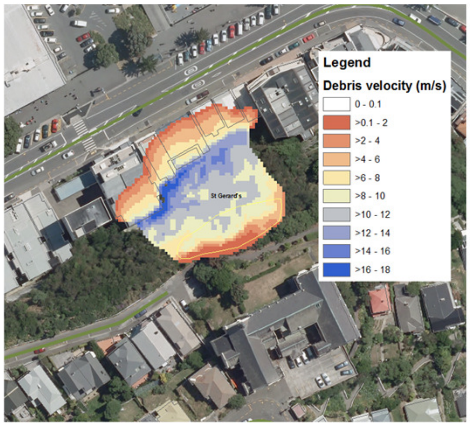


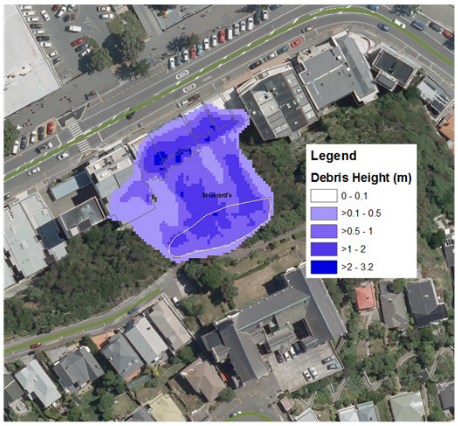
3D-static vs. dynamic modelled displacement

Static

Dynamic

Example site-specific assessment: St Gerard’s: Runout EQ (dry)





RAMMS 3D physically-based landslide runout model (model calibrated by back analysing >100 debris avalanches in greywacke)

Site specific assessments: Fill Laboratory testing

Aim: Replicate stress states in slopes and measure shear surface deformation mechanisms during:

1. Dynamic shaking (earthquakes)
2. Changing pore-water pressure (rainstorms)

Results:

- Fill slope failure style dependent on grain size characteristics and stress history of shear zone
- For looser coarser grained fills, lower pore water pressure was required for displacement to occur
- For finer grained and over-consolidated fills, required higher pore water pressures, but more likely to transition rapidly from creeping landslide to brittle failure → More likely to have flow type landslides
- Dynamic loading results in densification

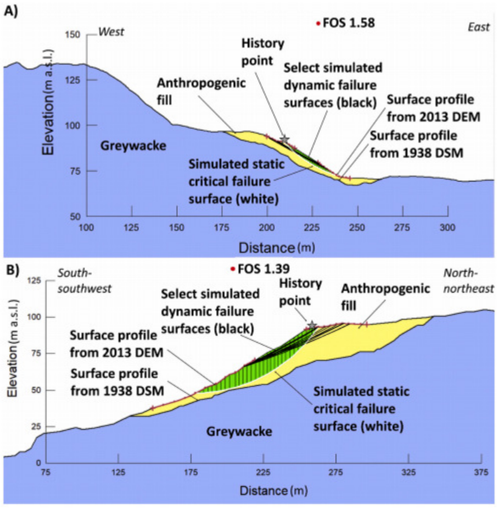
So, *in some instances*, fill slopes become stronger following earthquake shaking but this densification but it may make them more likely to be vulnerable to rapid debris flow-slides in future rainstorms.

Carey et al., 2021 Landslides

Numerical Modelling of Fill Slopes

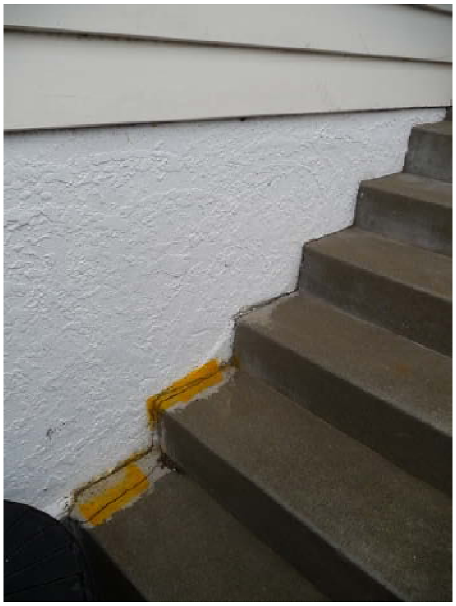
- **Aim:** Use static limit equilibrium and FE models and decoupled procedures (to calculate permanent ground displacement)

- **Results**:
  - Amount of displacement increases with PGA
  - Ranges from 0.01 m to 10 m displacement
  - For eq's with PGA's of >0.2 g, the displacement may not result catastrophic failure but can damage buried elastic pipes
  - Leakage water from broken pipes and increase in pore-water pressure results in **cascading hazards**
  - Orchy crescent: Larger deeper, finer grained fill body compared to Priscilla Crescent, and has larger simulated ground displacements → More unstable

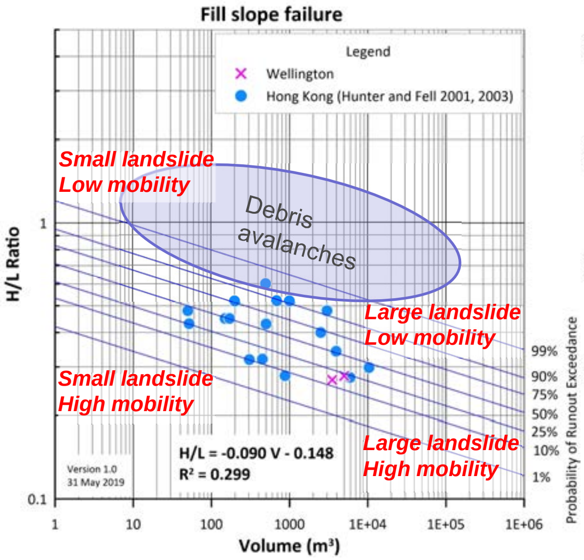


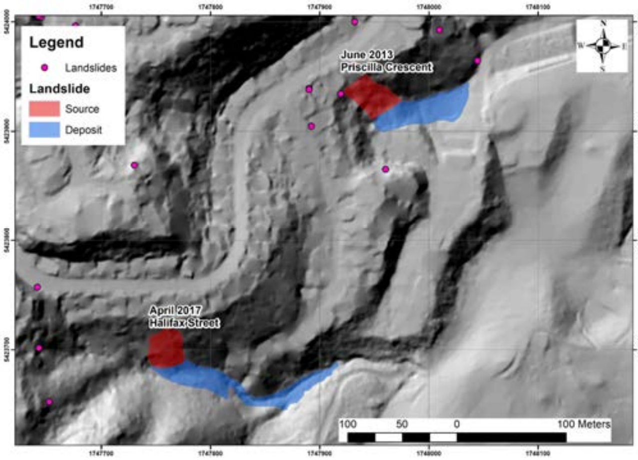
Brideau et al., 2021 Engineering Geology

Cascading hazards



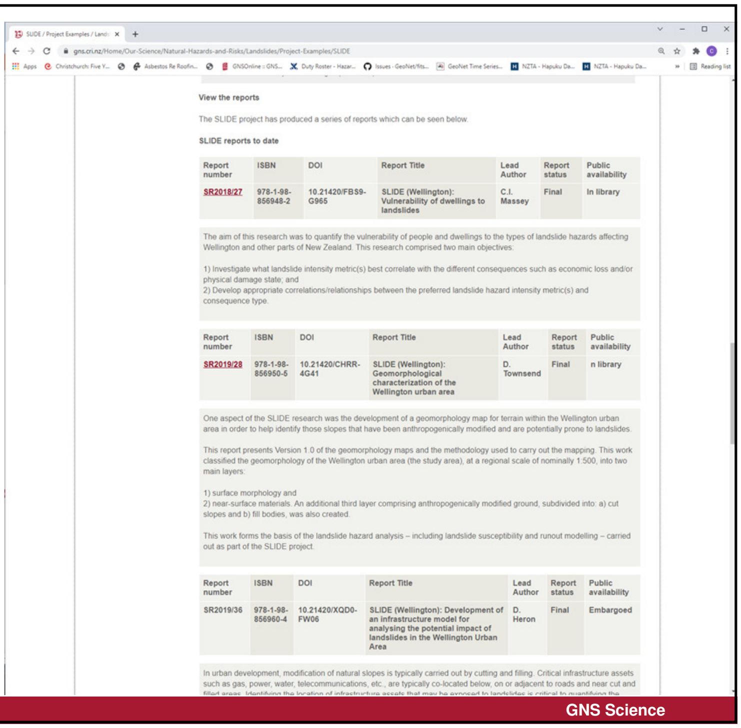
Cascading hazards: Fill slopes





Documents and papers

- **Search 'GNS slide project'**
  - Links to papers and reports
  - Down load data



View the reports

The SLIDE project has produced a series of reports which can be seen below.

SLIDE reports to date

Report number	ISBN	DOI	Report Title	Lead Author	Report status	Public availability
SR2018/27	978-1-98-856948-2	10.21420/FBS9-G965	SLIDE (Wellington): Vulnerability of dwellings to landslides	C.I. Massey	Final	In library

The aim of this research was to quantify the vulnerability of people and dwellings to the types of landslide hazards affecting Wellington and other parts of New Zealand. This research comprised two main objectives:

1) Investigate what landslide intensity metric(s) best correlate with the different consequences such as economic loss and/or physical damage state; and
2) Develop appropriate correlations/relationships between the preferred landslide hazard intensity metric(s) and consequence type.

Report number	ISBN	DOI	Report Title	Lead Author	Report status	Public availability
SR2019/28	978-1-98-856950-5	10.21420/CHRR-4G41	SLIDE (Wellington): Geomorphological characterization of the Wellington urban area	D. Townsend	Final	n library

One aspect of the SLIDE research was the development of a geomorphology map for terrain within the Wellington urban area in order to help identify those slopes that have been anthropogenically modified and are potentially prone to landslides.

This report presents Version 1.0 of the geomorphology maps and the methodology used to carry out the mapping. This work classified the geomorphology of the Wellington urban area (the study area), at a regional scale of nominally 1:500, into two main layers:

1) surface morphology and
2) near-surface materials. An additional third layer comprising anthropogenically modified ground, subdivided into: a) cut slopes and b) fill bodies, was also created.

This work forms the basis of the landslide hazard analysis – including landslide susceptibility and runout modelling – carried out as part of the SLIDE project.

Report number	ISBN	DOI	Report Title	Lead Author	Report status	Public availability
SR2019/36	978-1-98-856960-4	10.21420/XQD0-FW06	SLIDE (Wellington): Development of an infrastructure model for analysing the potential impact of landslides in the Wellington Urban Area	D. Heron	Final	Embargoed

In urban development, modification of natural slopes is typically carried out by cutting and filling. Critical infrastructure assets such as gas, power, water, telecommunications, etc., are typically co-located below, on or adjacent to roads and near cut and filled areas. Identifying the location of infrastructure assets that may be exposed to landslides is critical to quantifying the

Current research

This FY (June 2022)

- **Site-specific rock slope results (paper and report)**
- **RIL and Anthropogenic landslide paper**
- **Hazard-risk model report and paper**
- **Field- and lab testing of rock mass deformability and strength of jointed greywacke**
- **Dissemination of SLIDE results (IOF)**
- **JTC-1 Book on EIL (Towhata et al.)**

2022 to 2023

- **Shaking only damage ratios (EQC SOW4)**
- **Shaking + Permanent ground displacement damage ratios (EQC SOW4)**

Future research

- **Fill slopes**
  - More than 1,000 fill slopes mapped
  - Many not engineered
  - Many services (lifelines) are routed through them
  - Performed OK historically during rain
  - How will they perform during strong shaking
- **Retaining walls**
  - More than 4,000 identified
  - Many critical for building and infrastructure stability
  - Many not engineered