Resilience to Fault Displacement Hazards

White Paper

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Introduction

Despite recent surface rupturing earthquakes in New Zealand primarily impacting rural areas, fault-related ground deformation (displacement) caused significant damage to buildings and infrastructure (Van Dissen et al., 2012; Van Dissen et al., 2019; Fig. 1). Surface deformation also increased the intensity and spatial extent of secondary hazards like landslides (Bloom et al., 2021; Singeisen et al., 2024), river avulsion (Quigley and Duffy, 2020; McEwan et al., 2023), and long-term river and coastal flood susceptibility (Hughes et al., 2015; Quigley and Duffy, 2020; Delano et al., 2023). Active fault zones intersect buildings and critical infrastructure around Aotearoa New Zealand (NZ) – these 'nodes' represent the locations of enhanced demands on structures and the source of potential cascading lifeline failures in future events. However, hazard from fault surface rupture is not currently addressed in New Zealand legislation or building codes.

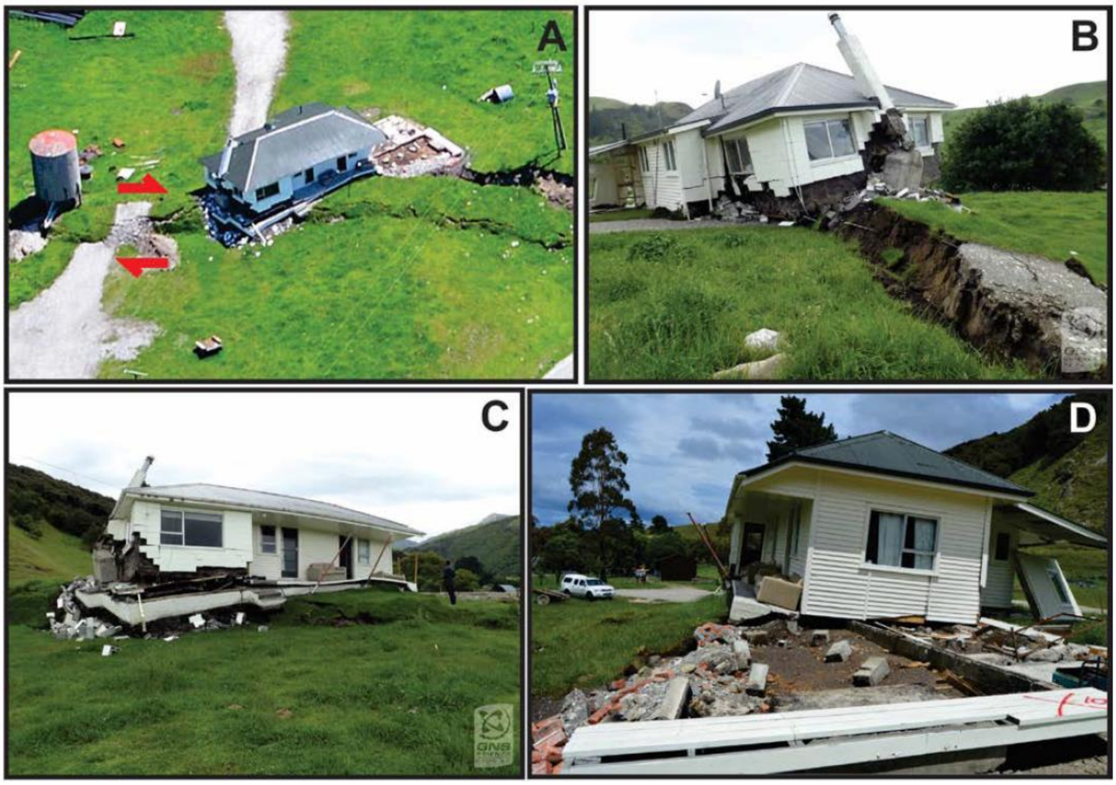

Figure 1: A 'direct hit' – a residential structure is displaced off its foundation by c. 10 m due to deformation on the Kekerengu Fault in the 2016 M7.8 Kaikōura Earthquake. There are numerous examples of residential-type structures and infrastructure like transport networks being damaged in New Zealand's historical earthquakes (figure modified after Van Dissen et al., 2019).

New Zealand has ~500 on-land active faults, >50% of which were mapped prior to the availability of high-resolution lidar topography (Litchfield et al., 2014; 2024a; Seebeck et al. 2024). The country is currently working towards c. 80% lidar coverage, initial releases of which have revealed more faults and fault complexity than previously identified (e.g., Barrell, 2019; Langridge and Morgenstern, 2019; Litchfield et al. 2022). Preliminary estimates have identified tens of thousands of residential structures within 200 m of an active fault (Wotherspoon, in prep.). Annual population growth of up to c. 3% and a housing shortage have increased rates of development natonally in recent years, exposing new buildings and services to displacement hazard (Huang and Leung, 2023; StatsNZ, 2023; 2024). This development commonly erases the geomorphic signature of faulting preserved in the natural landscape. Simultaneously, the need to upgrade distributed infrastructure such as water systems in many regions will drastically increase financial exposure to fault displacement hazards.

Given the step-change in data quality, increasing exposure to fault displacement hazard, *and* a decreasing ability to characterise it through time due to landscape modification, there is currently a critical time window in which to address this peril. This time-sensitivity distinguishes fault displacement from other hazards. Fortunately, the risks associated with fault rupture can be successfully mitigated with a range of established strategies, including better mapping, land use planning, probabilistic fault displacement hazard analysis (PFDHA), multi-hazard and risk models, and engineering design.

The purpose of this white paper is to steer the next generation of interdisciplinary research that will mitigate fault displacement risk and improve life safety and post-event functionality during and after large NZ earthquakes. It summarises and incorporates the outcomes of two workshops in April and May 2024[1] with stakeholders and researchers. We first discuss the regulatory and scientific context for the workshops, and then analyse the major themes, challenges, and possible solutions that were discussed. We conclude by assessing the value proposition of future work and propose a framework to guide future research investment.

Scientific and Engineering Context

Overarching Issues

Definitions of hazard and risk can vary between disciplines. In this white paper, hazards are phenomena with the potential to do harm, but 'hazard' is also used to refer to the likelihood or intensity of that phenomenon. Hazards can be primary or secondary. In the context of earthquakes, primary hazards are shaking and tectonic ground deformation. Secondary hazards include processes brought on by those two – e.g., liquefaction, landslides, tsunami, and flooding. Risk is typically defined as the product of likelihood (or hazard) and consequence, but can also refer to the effect of uncertainty on objectives.

Fault displacement hazards are herein defined as processes associated with tectonic ground deformation near faults that have the potential to disrupt or damage the built environment. In the strictest sense, fault displacement concerns surface fault rupture and folding of the Earth's surface as a result of fault slip. This deformation can directly impart strains on infrastructure and buildings. Coseismic hazards associated with faulting include slope instability compounded or accommodated by fault displacement (e.g. Bloom et al., 2021; Singeisen et al., 2024) and flooding as the result of river avulsion and/or regional tectonic subsidence (e.g. Townsend et al. 2015; Hughes et al., 2015; McEwan et al., 2023; Delano et al., 2023). Identifying and mitigating the effects of these primary and secondary hazards at any given site requires a range of disciplines and established tools (Fig. 2).

[1] The April workshop was focused on a stakeholder workshop (Litchfield et al., 2024b), whereas the May workshop was focused on fault displacement hazard and is summarised in this report.

LAND USE PLANNING
· Avoid areas with the potential for surface fault rupture
ENGINEERING GEOLOGY
· Identify and avoid primary faults · Establish non-arbitrary setbacks based on fault and ground conditions · Estimate amount and type of potential fault displacement
GEOTECHNICAL ENGINEERING
· Construct ductile earth fills to spread out fault displacement · Install soil reinforcement · Use slip layers to decouple ground movements from foundation · Keep the base of all foundation elements at the same elevation · Avoid protrusions that would act like cleats to lock the building into the ground · Place compressible materials adjacent to walls and utilities
STRUCTURAL ENGINEERING
· Design strong, ductile foundations, such as thickened reinforced mat foundations, waffle slabs, and post-tensioned slabs · Do not use piles or piers that tie structure into the ground · Design structure to be flexible and with isolation joints · Install "catcher bents" or ties for bridge spans that must cross over faults

Figure 2: "Defensive measures for accommodating surface fault rupture" (Bray, 2009).

Simply put, the approaches in Fig. 2 help to characterise hazard (e.g. Probabilistic Fault Displacement Hazard Analysis, PFDHA), reduce exposure (e.g. fault avoidance zones), and/or minimise the vulnerability (e.g. engineering design) of different built environment components (buildings and critical infrastructure). Although employing these approaches can effectively mitigate risk, a number of outstanding challenges remain:

- Updating and standardising empirical relationships for PFDHA based on NZ and global historical earthquake data
- Making use of physics-based models in PFDHA
- Developing fragility functions for a range of built environment components
- Identifying and implementing low-cost design solutions, including retrofits for built environment components
- Laboratory and computational testing of built environment component performance in response to fault deformation
- Integrating secondary and multi-hazards into risk mitigation
- Broadening site-specific hazard and risk analyses to regional scale, e.g. systems engineering approaches to linear infrastructure and emergency management plans
- Integrating engineering and PFDHA into land use planning to avoid overly prescriptive and/or conservative approaches to avoidance
- Responsible data-sharing to ensure standard approaches at the national level
- Providing useful, usable, and used guidance for a range of stakeholders that remains (i) scientifically robust and (ii) consistent at the national level
- Providing clear lines of communication between disciplines and sectors
- Growing national capability and capacity to conduct robust site evaluations

Overall, these challenges require a strategic, interdisciplinary, and well-communicated approach that draws on the expertise of geoscientists, engineers, planners, and stakeholders across sectors – universities, crown research institutes (CRIs), industry, and government.

Key Datasets and Analyses

Active Fault Databases: A primary dataset that underpins fault displacement hazard is an active fault database. A database stores information on the geospatial location of faults, their single event displacements, recurrence intervals, and other relevant characteristics. Active fault databases are used as a starting point for land use planning efforts like demarcating avoidance zones (Kerr et al., 2003) and for guiding site-specific geological and engineering investigations. The quality of such a dataset depends on the resolution of the data used to map the fault, the resolution and quality of the mapping itself, and the availability of high-quality paleoseismic site investigations.

In New Zealand, GNS Science maintains several forms of active fault databases for different purposes (https://data.gns.cri.nz/metadata/srv/eng/catalog.search#/metadata/d3790acb-756a-4984-90dc-9c7e9a501a9c; Litchfield et al., 2014, 2024a; Langridge et al., 2016; Bretherton et al., 2023; Seebeck et al., 2024). However, the highest resolution version of the database and recent fault mapping (in particular in the South Island) relevant to site-specific fault displacement hazard are not currently publicly available in the GNS webmap (https://data.gns.cri.nz/af/; Litchfield et al., 2024b), although they are available in selected districts/regions (Bretherton et al., 2023https://gis.hbrc.govt.nz/hazards/; https://mapping.gw.govt.nz/GW/GWpublicMap_Mobile/?webmap=fd376f8082924e6fa3246ef195fe2312). The active fault database webmap is being updated to link datasets such as the NZ Community Fault Model (Seebeck et al., 2024) and the New Zealand Paleoseismic Site Database (Litchfield et al., 2024a)

Probabilistic Fault Displacement Hazard Analysis (PFDHA): PFDHA is a statistical method of quantifying the rate and intensity of displacement near faults (Youngs et al., 2003). In the analysis, hazard is defined as the annualised probability of exceeding different values of displacement. The primary inputs are knowledge of the site's position relative to active faults, magnitude-dependent probability of surface rupture, recurrence interval, and single event displacements. Each of these inputs can be quantified via site-specific investigations of paleoseismic events (the displacement approach) and/or empirical approaches based on surface rupturing earthquake inventories (the earthquake approach). The primary output is a hazard curve, which makes PFDHA analogous to probabilistic seismic hazard analysis (or PSHA) but with some important differences. Because being able to quantify hazard is fundamental to any decision making process regarding building near active faults, we describe hazard calculations in more depth below.

Hazard curves are used to communicate the annualized hazard of earthquake strong ground motions, earthquake surface fault rupture, and other natural hazards. They all have the same characteristics that can be generalised for discussion purposes. When the likelihood of a hazard is calculated, it is often the product of several contributing variables (e.g., Equation 1 for surface fault rupture hazard after Moss et al., 2022):

$$\upsilon\upsilon(D_0) = \alpha \int_{m,s}^{\square} f_{M,S}(m,s)\, P^*(D > D_0|m, x/L)\, dmds \tag{1}$$

where $\upsilon(D_0)$ is the mean annual rate of exceeding a specified displacement; α is the mean annual rate of earthquakes of magnitudes m; $f_{M,S}(m,s)$ is the probability distribution of earthquake magnitude (m) and surface rupture location (s) on the fault source; x is distance along the length L of the fault rupture; $P^*(D > D_0|m, x/L)$ is the probability that displacement D at the site exceeds the specified level D_0. These variables are represented as probability distributions, thereby quantifying the central tendency (mean, median) and dispersion (standard deviation, coefficient of variation) of the hazard. When probability distributions are multiplied together, regardless of the initial distributions, the resulting probability distribution function (PDF) approaches the lognormal distribution as the number of multiplied distributions increases. This is an extension of the Central Limit Theorem in log space (Ang and Tang, 2007; Moss, 2020). The lognormal distribution is also a useful distribution in general for values that cannot be negative such as ground motions or fault displacements. Figure 3 shows the lognormal distribution in arithmetic space and in semi-log space for some hazard value y. The lognormal distribution is by definition normally distributed in semi-log space.

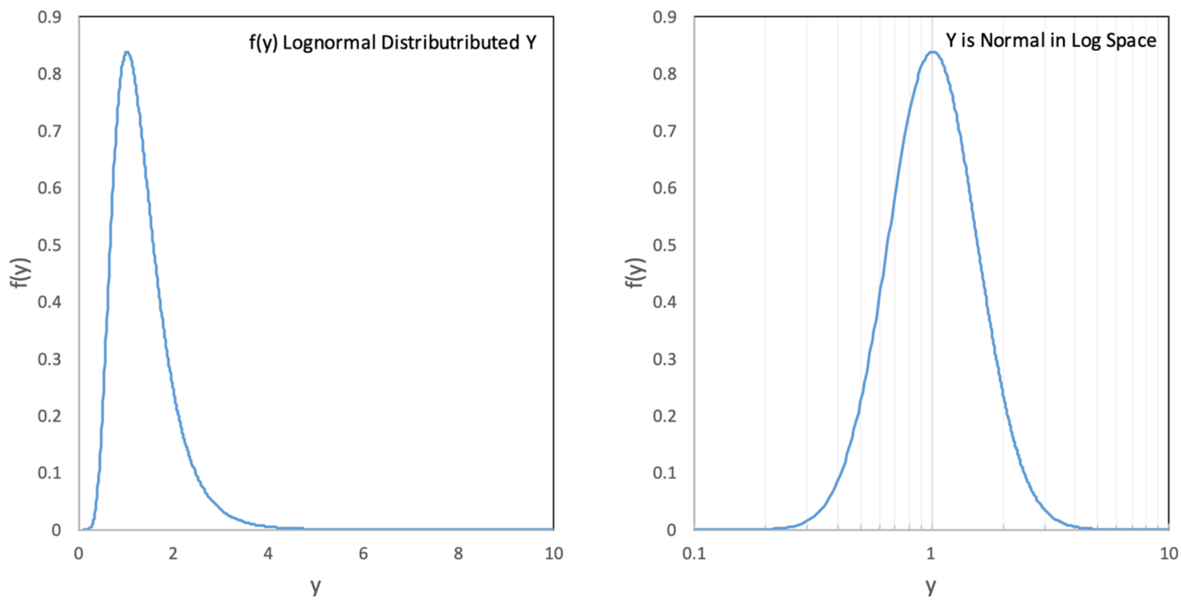

Figure 3: Lognormal distribution in arithmetic (left) and semi-log space (right).

In seismic hazard and risk analyses, we are interested in the level of ground shaking or fault displacement exceeding some design threshold. The probability of exceedance is represented probabilistically as the complement of the cumulative distribution function (CDF). Figure 4 shows the cumulative lognormal distribution and the complement of the cumulative lognormal distribution in semi-log space. The right plot in Figure 4 is showing the probability of exceedance, P(Y>y).

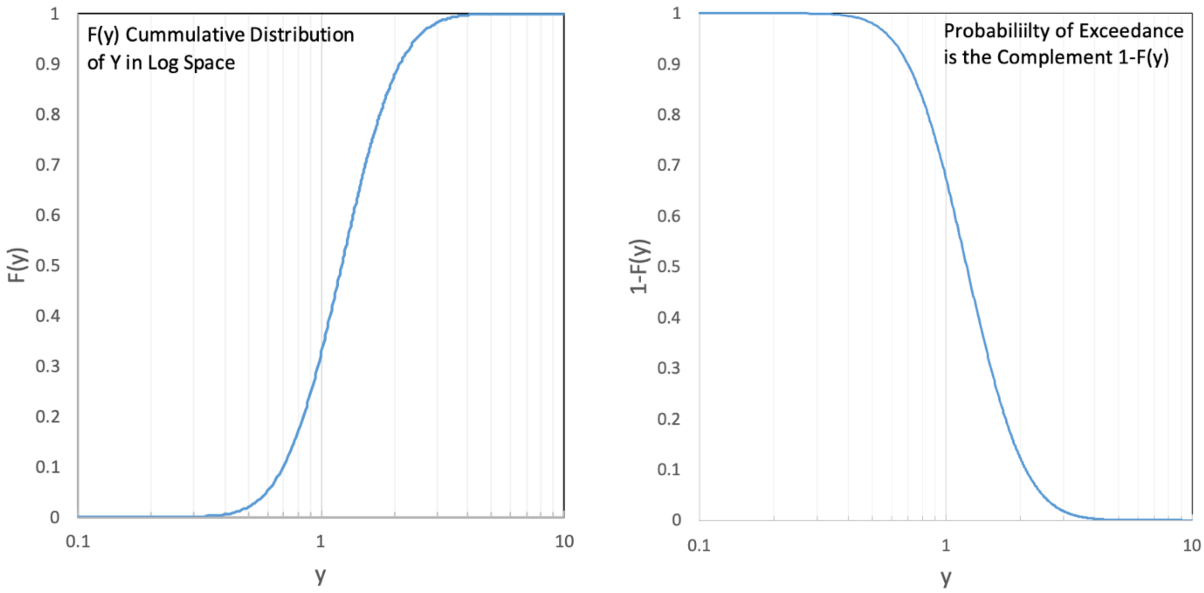

Figure 4: Cumulative lognormal distribution (left) and complement of cumulative lognormal distribution (right) in semi-log space.

Finally, to get the annual rate of exceedance of the hazard, we multiply the complementary probability distribution by the mean rate of the hazard λ, as shown in Figure 5.

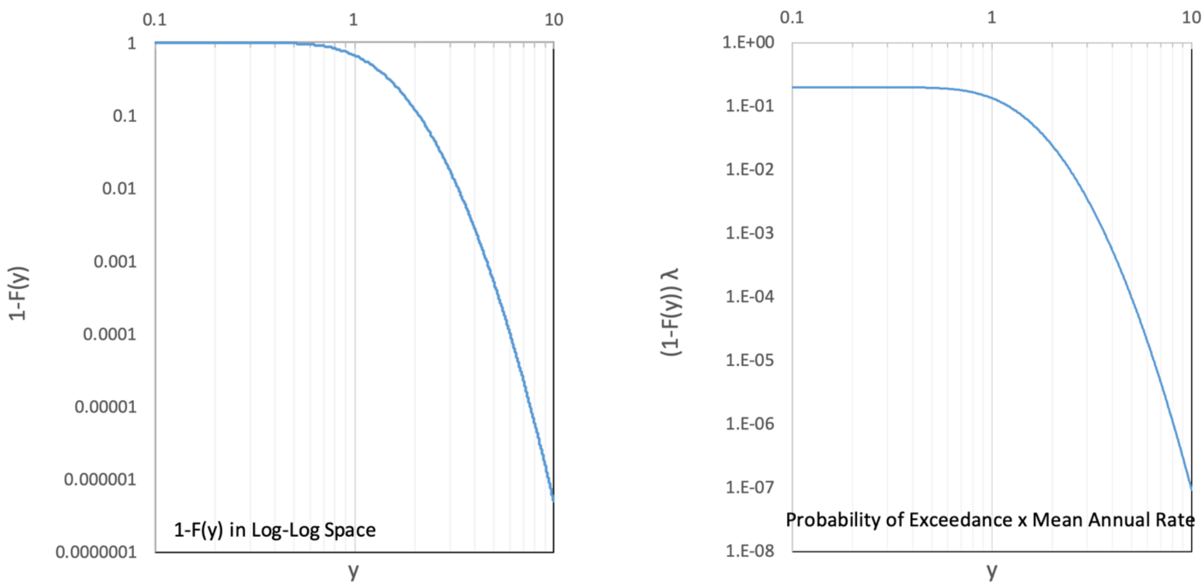

Figure 5: Hazard curves - the complement of cumulative lognormal distribution in log-log space (left) and the same now multiplied by the mean annual rate (right) to get the mean annual rate of exceedance.

The resulting hazard curve is now in the familiar format that we see when presented with hazard calculations. The x-axis is the hazard metric we are concerned about exceeding and the y-axis is the annual probability of exceedance.

The annual probability of exceedance (AEP) levels used for design are often spelled out in codes, but these are ultimately determined by what a society finds as an acceptable level for specific hazards. For example, for most commercial airlines the acceptable level is set at less than 10^{-4} based on decades of flying and the annualized rate of accidents with fatalities. Minimum floor levels for most new construction require consideration of 10^{-2} (100 yr return period) flood levels. In many countries, the design level for strong ground shaking is set at just above 10^{-3} for typical construction (2.105×10^{-3} = 10% in 50 yr = 475 yr return period). Currently, there is no consensus on the acceptable AEPs that should be set for surface fault rupture, but some agencies have used 10^{-3} (1000 yr return period) as a starting point.

Discussions of acceptable levels of AEPs should be tied closely to the performance of specific infrastructure and the desired post-event performance. Discussing specific design values of ground shaking or fault displacement is not productive unless we know how built environment components can accommodate the demands from these hazards.

Multi-hazard and Risk Models: Fault displacement can directly or indirectly impact the built environment. For direct impacts, PFDHA is the tool used to characterise hazard. For indirect impacts, such as those from secondary hazards or from cascading critical infrastructure failures as a result of fault deformation, the range of existing tools is far more limited.

Cascading hazard models include computational models of slope instability and hydrological responses to fault deformation. An example would be the Natural Hazards Commission Toka Tū Ake (NHC; formerly referred to as the Earthquake Commission - EQC) Increased Flood Vulnerability assessments based on post-Canterbury Earthquake Sequence flood modelling (which included tectonic subsidence in Christchurch; Tonkin and Taylor, 2014). Likewise, research from the 2016 Kaikōura earthquake has highlighted how proximity to fault deformation can influence the spatial distribution and failure mechanisms of landslides (Bloom et al., 2021; Singeisen et al., 2024).

Models representing the performance/damage of single built environment components allow for quantification of the implications in close vicinity to fault rupture. However, to capture the wider implications of fault rupture on critical infrastructure networks, models should capture the cascading outages throughout networks. These models reveal the dependencies between infrastructure networks, where loss of service in one network leads to outages in others that rely on that service.

Both these families of models are important because fault displacement is commonly neglected in regional planning and emergency management plans for large earthquakes. For instance, a recent effort by Daglish (2024) used principles of regional seismic hazard analysis to quantify the New Zealand road network's exposure to fault displacement hazard. Internationally, there has not been much work in this space. Multi-hazard and risk modelling are areas of research expertise in New Zealand and this capability should be translated to fault displacement hazard.

Key International Initiatives

The May workshop focused on recent international progress in PFDHA and on current practice in New Zealand. International delegates from research groups around the world were invited to speak on different topics, participated in an expert panel Q&A, and contributed to the workshop sessions. All speakers were integral parts of recent (last 5 years) initiatives focused on improving PFDHA. Below, we summarise some of the key contributions of the international experts.

Californian-led Fault Displacement Hazard Initiative (FDHI): The FDHI is housed at the University of California Los Angeles, but it involves c. 30 researchers from several California-based universities and companies (https://www.risksciences.ucla.edu/nhr3/fdhi/home). Most work to date has focused on improving empirical relationships and workflows that underpin the 'earthquake' approach of PFDHA. This has resulted in review and data wrangling for 75 shallow crustal surface rupturing earthquakes, containing >40,000 field-based displacement measurements on principal and distributed ruptures. The FDHI modelling teams have considered and solved several challenges of PFDHA:

- how to standardise geospatial control on rupture maps
- how to sum offsets across principal and/or distributed ruptures
- how to handle nonlinear Displacement-Magnitude scaling
- and how to best define 'maximum displacement'

The updated models have more robust statistical frameworks and less aleatory variability than previous models.

Aligned research conducted by FDHI investigators include better physical and computational models of fault displacement that quantify the effects of different variables: magnitude, depth to rupture plane, fault dip, slip sense, and material stiffness. Some of these variables are not well-accounted for in PFDHA. For example, fault slip in geologically 'loose' and strain hardening material leads to wider shear band formation, and thus more distributed deformation, than in geologically 'stiff' and strain softening material. This research has opened the possibility of using metrics like Vs30 (i.e. the time-averaged shear-wave velocity from 0-30 m depth) to characterise stiffness, which in turn affects the surface expression of faulting and surface strains.

A new approach to regional-scale PFDHA was also presented. Typically, PFDHA is based on empirical/statistical models and *site-specific* geological information. *Regional* hazard products can be useful as a system-level tool to better understand risk to critical infrastructure networks, and facilitate discussions regarding research priorities and needs. While such an approach is superficially analogous to a regional seismic hazard map (i.e. one showing exceedance probabilities of shaking intensity over a certain timescale), many of those well-understood principles do not translate well to displacement hazard at scale. There is also the concern that such a model could be confused with other fault 'polygons' such as Fault Avoidance Zones in New Zealand or Alquist-Priolo Special Study Areas in California. Nonetheless, the underlying hazard calculations and output hazard products could be extremely useful tools for stakeholders interested in (i) evaluating network-wide exposure to different levels of hazard and (ii) identifying priority areas for site-specific studies.

European-led Fault2SHA: Fault2SHA (https://fault2sha.net/) is an international and interdisciplinary working group on fault displacement hazard promoting collaboration between researchers and practitioners. One of its major achievements is an open source database of surface rupture maps and displacement measurements from 50 earthquakes globally (Surface Ruptures due to Earthquake or SURE; Nurminen et al., 2022). We note that the database does not currently include the 2016 Kaikōura earthquake, in part due to its complexity relative to other earthquakes in the catalogue.

Fault2SHA researchers have also made significant advances in specific parts of the PFDHA equation: conditional probability of surface rupture (the chance that fault rupture reaches the surface given a number of different variables) and handling distributed ruptures (discrete offsets at some distance from the principal fault). Traditionally, conditional probability of surface rupture is determined based on empirical relationships, which may be region-specific or global. There is large variability in how these relationships were constructed and quality control issues therein. A new analytical and semi-empirical approach was developed that demonstrates the importance of fault geometry, kinematics and seismogenic thickness in these magnitude-dependent conditional probabilities. The new model fits empirical curves from New Zealand.

Aligned research also developed a ranking scheme and various regressions for distributed ruptures in SURE2.0. The ranking scheme allowed researchers to evaluate the probability of different kinds of secondary faulting at distances away from the principal trace. The type of distributed rupture depends on fault kinematics and pre-existing geologic structures. Empirical regressions for probability of occurrence and displacement on secondary structures were developed. A decision tree can be used to help practitioners determine which regression to use with different a priori knowledge regarding the presence of pre-existing secondary faults.

Summary: Overall, the international speakers stressed the importance of (i) improving the statistical frameworks that underpin PFDHA; (ii) incorporating more geological knowledge into regressions and hazard model branches; (iii) taking a range of different approaches (field, laboratory, model) to PFDHA at different scales; and (iv) the need for better communication between geologists, hazard modellers, engineers, and end-users. Both groups have made significant advances in PFDHA over the last 5 years.

New Zealand's Regulatory Context

Ministry for the Environment Active Fault Guidelines (2003)

Kerr et al. (2003) set out guidelines to assist planners with decision-making regarding development near active faults. The guidelines provide a risk-based approach that considers fault characteristics like recurrence interval and fault complexity, as well as building importance, which includes measures of exposure, criticality, and vulnerability. The guidelines are focused on life safety and set out criteria for demarcating Fault Avoidance Zones.

Many stakeholders have remarked that the guidelines have been helpful in their regions and districts, although they are not always implemented consistently or at all because they are not legally binding (see also Bretherton et al. 2023). They also need updating to account for recent scientific (e.g. improved fault mapping and PFDHA) and engineering progress in characterising and accommodating fault displacement.

Further regulatory context is provided in the GNS Science Report from the April Workshop (Litchfield et al., 2024b), as well other recent analyses (Hale et al., 2017; Gunnell et al. 2022; Bretherton et al. 2023; Kelly et al. 2023).

Science, Engineering, and Stakeholder Considerations

May workshop participants were asked the following questions: *What are the most difficult challenges and research needs in FDHA? What are possible solutions? What are the FDHA barriers, opportunities, and needs facing practitioners, insurers, councils and communities?"*

Discussion from participants in the room and online from Geoscience Australia and University of Melbourne brought together a broad range of expertise and experience. There were four primary themes that emerged from the discussion (Table 1).

Challenge / Common Themes	Examples / Research Needs	Solutions
Lack of effective communication between scientists, engineers, social scientists, clients, and policy makers	How to distil complex information for different audiences – what kind of language is required before science and engineering ideas are understood by policy makers and vice versa? Example given by council hazard analyst: some people think Fault Avoidance Zones are related to shaking hazard.	Social science research to investigate the practical elements of effective communication specific to fault displacement hazards. Codevelop and update the MfE Guidelines.
Several sources of geologic uncertainty that carry through from databases to hazard calculations	How to differentiate between and account for areas that are unmapped, have low-quality mapping, have evidence of absence of faulting, or have subtle evidence of ground deformation.	Updated fault databases, better data sharing from client reports in a format like the NZ Geotechnical Database, and more research into features with long or erratic recurrence
Poor or incomplete understanding of fundamental processes underpinning PFDHA	How to integrate physics-based and analogue models with empirical analyses to better characterise influence of slip partitioning and soil geotechnical properties of fault surface expression	Interdisciplinary research that bridges gaps between approaches
Funding deficit and lack of capability to continue advancing the field	How to train more junior geologists and engineers qualified to undertake PFDHA and other critical hazard analyses	Research funding that repairs and expands the leaky pipeline of prospective engineering geologists and geotechnical engineers

A series of talks from New Zealand investigators supported these themes and highlighted additional research needs, barriers, and opportunities:

- Fault displacement can trigger or exacerbate other hazards such as flooding; physics-based models can be used to forecast such hazard ahead of events occurring;
- In places, lidar has significantly improved our understanding of fault location, complexity, and displacement hazard – the rollout of nationwide lidar is an asset;
- Tectonic setting (and complexity therein) exerts a strong control on large displacements in historical crustal earthquakes – more research is required to understand why;
- Faulting in volcanic regions is spatially and temporally complex, and presents a challenge to PFDHA – the quality and quantity of data we have in the Taupō Rift is world leading;

- Client needs and uncertainties are often budget-constrained – best practice can vary significantly between stable continental regions like Australia and tectonically-active regions like New Zealand;
- Even on well-studied faults, significant geological uncertainty can persist, to the extent that the locations of principal faults may not be definable after invasive investigations – guidance on best practice in these cases would be helpful.
- A range of engineering solutions exists for accommodating fault displacement for the purposes of life safety and post-event functionality – more work is required to look at performance and dependencies at a systems-level.

Based on the presentations, workshop discussions, and thematic analysis above, we constructed a conceptual diagram of what a productive research programme on fault displacement hazard would include (Fig. 6). In this conceptual model, there are three key disciplinary domains: Hazard and Risk Models, Engineering Design, and Policy & Land Use Planning. These domains feed into each other (arrows) and interact to work on specific outputs. These outputs contribute to broader outcomes (outer ring) that collectively build resilience to fault displacement hazards (centre).

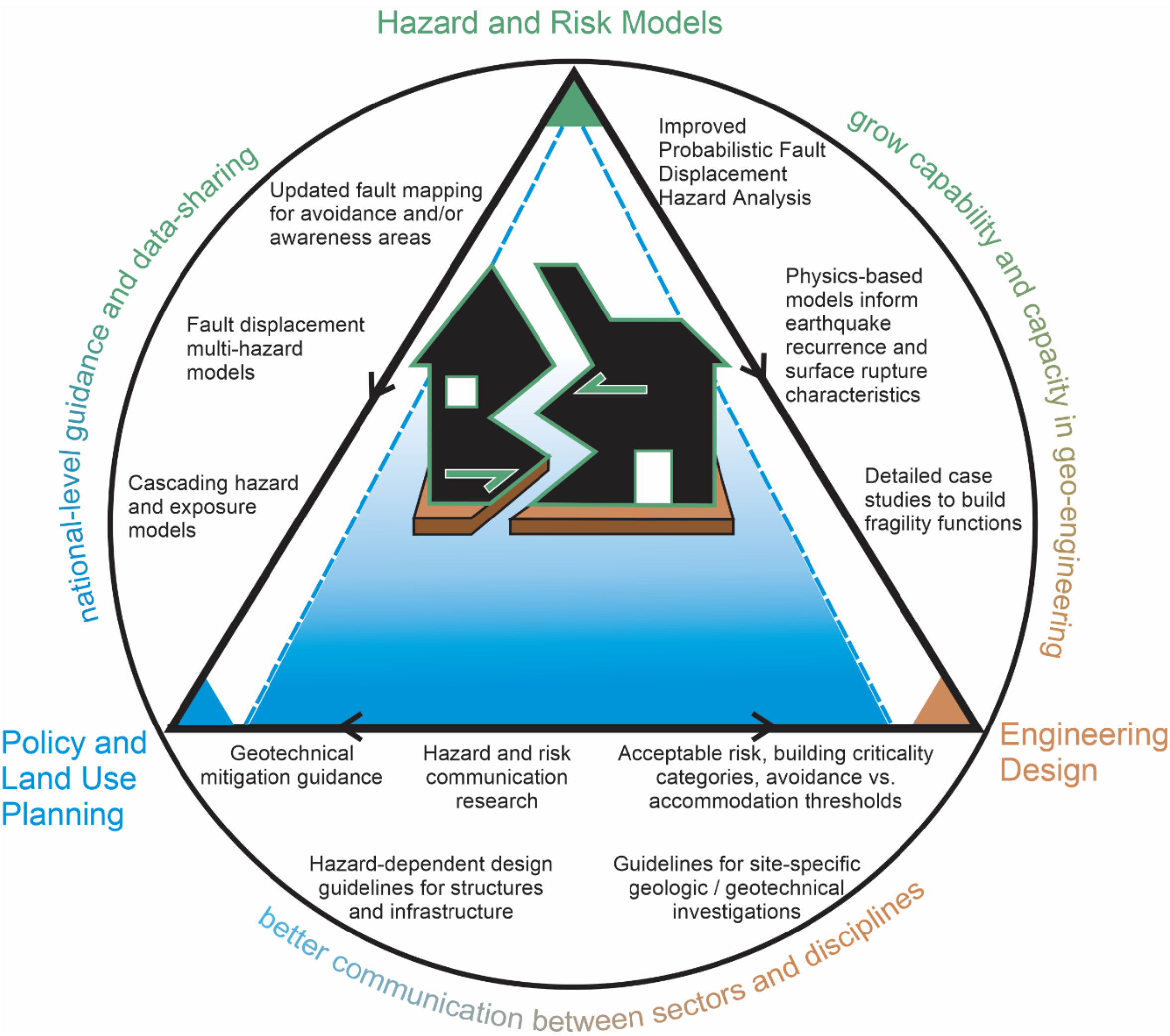

Figure 6: Conceptual diagram outlining the basic framework and key components of a productive, interdisciplinary research programme on fault displacement hazard. See text for description.

Value Proposition of an Interdisciplinary Research Programme

May workshop participants were asked the following question: *“Which actions (across various domains) would maximize benefit:cost ratio in terms of mitigating risk in New Zealand/Australia?”*

New Zealand is subject to a range of perils, including floods, volcanic eruptions, earthquakes, tsunami, and landslides. One of the emergent themes in this workshop session was how hazard analysts, insurers, and planners should rank fault displacement compared to other priorities. Below we incorporate some of these themes in a discussion of the value of a dedicated research programme on fault displacement hazard.

1) Accounting for fault displacement can be an easy win, or easy loss

Compared to other perils, fault displacement is a relatively well-constrained problem. Geologists can map active faults on high-resolution lidar and subsurface datasets; investigate their rates of activity and range of coseismic offsets; and employ various probabilistic models to account for unobservable distributed deformation and secondary hazards (e.g. Delano, 2024). In other words, hazard and exposure are readily quantifiable and spatially constrained (noting that there are significant uncertainties in applying empirical approaches to any new site). This makes mitigation measures such as avoidance, accommodation, or planning for rapid post-event repair relatively straightforward.

After a large earthquake, emergency managers have to prioritise resources based on the locations of the damage incurred and post-event functionality of services. Not accounting for displacement on faults and the associated hazards that it intensifies will increase the footprint of coseismic consequences and decrease the provision of essential critical infrastructure services. In many cases, pre-event measures can be taken to (i) decrease the duration and magnitude of service loss; (ii) decrease the repair costs or provide redundancies for critical infrastructure services; and (iii) decrease the likelihood and magnitude of damage to structures near faults. In places where mitigation is not possible, emergency management plans that account for the locations and intensities of displacement-related disruptions will result in better decision-making.

Thus, relative to other perils that may have greater overall consequence in many regions, accounting for fault displacement can be easy to accomplish and has broad benefit (both spatially and across various assets).

2) Fault displacement causes and compounds other hazards

There is clear statistical and mechanistic evidence that fault displacement and reduction of rock mass strength within fault zones increases the likelihood of coseismic slope instability, as well as river and coastal floods. Despite the clear links, these cascading and compounding hazards are rarely considered in planning and engineering. New Zealand has one of the best natural laboratories in the world for this problem because of the numerous multi-hazard case studies in historical events.

Future surface-deforming events will spur chains of multiple hazards, but we do not currently account for multi-hazard chains associated with faulting (Stahl et al., 2023). The New Zealand’s landscape and recent events are key research assets.

3) Even small displacements can significantly impact the resilience of systems

The performance of engineered structures when exposed to fault displacement can vary significantly. From a life safety perspective, single story, regularly-shaped, timber-framed houses fare exceptionally well in response to significant coseismic strains near faults (e.g. Fig. 1; Van Dissen et al., 2019). However, even small amounts of far-field tilt, such as centimetres of subsidence expressed over many kilometres, can render assets like gravity-assisted water infrastructure inoperable in terms of post-event functionality. Significant uplift or subsidence near the coast can cause saltwater intrusion into wells and inundation of coastal infrastructure. Displacement can also destabilise flood protection measures like stopbanks. In some cases, loss of functionality in one utility, such as provision of water or power, can have cascading effects across others.

Although the spatial footprint of mapped surface faulting is small in comparison to total land area, fault displacement hazard can influence a much broader area because of widely varying built environment characteristics and cascading failures.

4) The best time for research and action is now

Fault displacement hazard is usually dealt with on a site-by-site or client-by-client basis. This approach leads to widely varying practices and quality of investigations. Given (i) the recent scientific advances of overseas colleagues and NZ investigators, (ii) the increase in high-resolution topography and ability to characterise faults; (iii) the demand to expand development for housing and services; and (iv) the lack of modern, legally-binding guidance for developing near active faults and (v) the demand for suitably skilled geotechnical engineers and engineering geologists across New Zealand (e.g., NZGS, 2024) , **there is a need for NZ-specific national standards underpinned by the best available science. There is currently a time-sensitive window in which to invest in an interdisciplinary research and capability-building programme on fault displacement hazard.**

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Appendix 1 – QuakeCoRE FDHA Workshop (May 2024) Attendees and Schedule

Name	Organisation	Role
Paolo Boncio	Uni. Chieta di Pescara	Geologist
Rose Coulter	AECOM New Zealand	Engineering Geologist
Aasha Pancha	Aurecon NZ Ltd	Engineering Geologist
Paul Wopereis	BECA	Engineering Geologist
Abilash Pokhrel	BECA	Geotechnical
Robb Moss	Cal Poly San Luis Obispo	Geological Engineer
Helen Jack	Environment Canterbury	Hazards Manager
Tabitha Bushell	NHC	Risk Reduction and Resilience
Natalie Balfour	NHC	Risk Reduction and Resilience
Jonathan Griffin	Geoscience Australia	Geologist/ Hazard Scientist
Dan Clark	Geoscience Australia	Geologist
Tamarah King	Geoscience Australia	Hazard Scientist
Brendan Duffy	GHD	Engineering Geologist
Matt Howard	GHD	Engineering Geologist
Rob Langridge	GNS	Geologist
Russ Van Dissen	GNS Science	Geologist
Pilar Villamor	GNS Science	Geologist
Genevieve Coffey	GNS Science	Geologist
Chris Rollins	GNS Science	Geophysicist
Kate Clark	GNS Science	Geologist
Nicola Litchfield	GNS Science	Geologist
Stephen Thompson	Lettis Consultants International	Engineering Geologist
Mark Willard	Ministry of Education	Structural Engineer
Roger Fairclough	NEO LEAF GLOBAL	Infrastructure Specialist
Fiia Nurminen	Rina Consulting	Geologist
Dee Ninis	Seismology Research Centre	Geologist / Hazard Scientist
Nick Peters	Tonkin & Taylor Ltd	Engineering Geologist
Mike Jacka	Tonkin + Taylor	Engineering Geologist
Cole Brown	Tonkin + Taylor	Engineering Geologist
Alex Sarmiento	UCLA	Engineer / Hazard Scientist
Carol Canora Catalán	Uni. Autónoma de Madrid	Geologist
Liam Wotherspoon	University of Auckland	Geotechnical Engineer
Kayley Crawford-Flett	University of Auckland	Geotechnical Engineer
Tim Stahl	University of Canterbury	Geologist
Andy Nicol	University Of Canterbury	Geologist
Erin McEwan	University Of Canterbury	Geologist
Abbie Underwood	University Of Canterbury	Geologist
Jaime Delano	University Of Canterbury	Geologist
Brendon Bradley	University of Canterbury	Earthquake Engineer
Yunqi Huang	University of Melbourne	Geologist
Mark Quigley	University of Melbourne	Geologist
Gideon Tang	University of Melbourne	Geologist
Ambica Sharma	University of Melbourne	Geologist
James La Greca	University of Melbourne	Geologist
Mark Stirling	University of Otago	Geologist
Alex Travers	University of Otago	Geologist
Rick Wentz	Wentz-Pacific Limited	Geotechnical Engineer
Tim McMorran	WSP	Engineering Geologist
Jeff Fraser	WSP New Zealand	Engineering Geologist

QUAKECORE FAULT DISPLACEMENT HAZARD WORKSHOP

QuakeCoRE
NZ Centre for Earthquake Resilience
Te Hiranga Rū

15-17 May 2024

OVERVIEW
Recent ground-surface rupturing earthquakes in New Zealand (Edgecumbe, Darfield, Kaikōura) have primarily affected rural areas, but active fault zones intersect buildings and critical infrastructure around NZ. Mitigating future fault rupture will require a range of strategies such as land use planning, engineering geology, civil engineering, and structural design. This workshop is intended to facilitate discussions and planning for the next generation of mitigating fault displacement risk in NZ by building on in-country expertise and the recent advances of our international colleagues. The purpose is to build a community of practice and plan for future research on fault displacement hazard and risk.

DAY 1 - MAY 15TH		
TIME	**SPEAKER / ACTIVITY**	**TOPIC**
9:00	Workshop organisers and participants	Welcome and Introductions

VENUE KEY INFORMATION

University of Canterbury

John Britten Conference Foyer 102, 69 Creyke Road, Ilam, Christchurch 8041

Parking   Campus Maps

SCHEDULE AT-A-GLANCE

y 1: New Zealand context; International perspectives and scientific state-of-the-art

y 2: Technical talks and strategic planning

Day 3: Field trip

ORGANISERS

9:50	Brendon Bradley **(University of Canterbury; QuakeCoRE)**	An overview of QuakeCoRE
10:00	Natalie Balfour **(Toka Tū Ake)**	NHC's role as national insurer and research priorities
10:10	Russ Van Dissen **(GNS)**	Examples of surface fault rupture impacts on engineered structures in New Zealand and an overview of the NZ Ministry for the Environment's 2003 "Active Fault Guidelines"
10:30	**Morning Tea**	
11:10	Alex Sarmiento **(University of California Los Angeles)**	New Fault Displacement Models from the FDHI Project

Stahl (University of Canterbury), Liam Wotherspoon (University of Auckland), Nicola Litchfield (GNS), Jeff Fraser (WSP)

PARTICIPANTS

ange of speakers and attendees from consultancies, universities, CRIs, councils, and government organisations

11:30	Paolo Boncio **(Università di Chieti-Pescara)**	The Fault2SHA activity on Fault Displacement Hazard Analysis
11:50	Fiia Nurminen **(RINA Consulting)**	Distributed surface rupturing hazard
12:10	**Lunch**	
13:00	Robb Moss **(CalPoly San Luis Obispo)**	Forecasting Reverse Fault Rupture: Experiments, Modeling, Analysis, and PFDHA
13:20	Steve Thompson **(Lettis Consultants International)**	New Fault Displacement Models from the FDHI Project

13:40	**International Expert Panel**	**Panel discussion and Q&A**
14:20	**Afternoon Tea**	
14:50	**Workshop Session 1**	**Global and local scientific challenges and opportunities in FDHA**
15:50	Organisers	Closing Remarks

DAY 2 - MAY 16TH		
TIME	**SPEAKER / ACTIVITY**	**TOPIC**
9:00	Organisers	Welcome and Recap
9:10	Erin McEwan **(University of Canterbury)**	Coseismic river response to surface displacement: case studies and models
9:30	Rob Langridge **(GNS)**	Alpine Fault displacement, slip partitioning and avoidance zone mapping: Developments since 2009.
9:50	Chris Rollins **(GNS)**	Anomalously large fault displacements in different tectonic settings
10:10	**Morning Tea**	
10:50	Pilar Villamor **(GNS)**	Complex faulting in the volcano-tectonic environment of the Taupō Rift

11:10	Rose Coulter **(AECOM)**	Differences in earthquake geology in Stable Continent Regions vs Plate Boundary Regions, a consultant's perspective
11:30	Nick Peters **(Tonkin and Taylor)**	Case studies of desktop and intrusive investigations resulting in different mitigation measures
11:50	Liam Wotherspoon **(University of Auckland)**	Fault rupture in New Zealand: Impacts, exposure and design
12:10	**Lunch**	
13:00	**Workshop Session 2**	**Stakeholder and end-user needs**
14:00	**Afternoon Tea**	
14:30	**Workshop Session 3**	**Strategic planning - prioritise actions across disciplines**

15:30	Organisers	Closing, Field Trip, Dinner
17:30	Conference Dinner - Dux Central	

DAY 3 - MAY 17TH FIELD TRIP TO NORTH CANTERBURY
DEPART UNIVERSITY OF CANTERBURY FROM ENGINEERING ROAD AT 8:00 AM; ARRIVE BACK AT ENGINEERING ROAD BETWEEN 5:00 AND 6:00 PM
PACKED LUNCHES PROVIDED