Surface rupture hazard zonation: best practice for New Zealand?

D.D. Hale, C.H. Fenton & N. Khajavi

Department of Geological Sciences, University of Canterbury, Christchurch

ABSTRACT: Engineered structures crossing active faults are vulnerable to damage during surface faulting earthquakes (e.g. Darfield 2010; Kaikoura 2016). The design and location of mitigation measures to counteract fault rupture requires detailed knowledge of the location of the active fault traces, fault geometry, including the width of the fault zone at the surface, and the distribution of strain within the fault zone. The current understanding of fault geometry and displacement profiles is based on predominantly subsurface data through essentially isotropic ground conditions. Although empirical relationships among fault parameters, such as rupture length, earthquake magnitude and average or maximum displacement, can be used to characterise potential surface rupture hazard for an entire fault zone, the behaviour of a fault at a specific location, as is required for engineering design, can be harder to forecast. For hazard planning and front-end engineering design, rupture zonation is a useful approach (e.g., NZ Ministry for the Environment; California's Alquist-Priolo Zonation maps). To produce meaningful fault rupture zonation maps requires an integration of data on tectonic geomorphology, paleoseismology, and both crustal and near-surface fault geometry. Rather than define narrow prescriptive fault avoidance zones, a better approach is to develop a broader zonation that highlight areas where there is the need for detailed fault rupture mitigation studies to be performed for all significant developments.

1 INTRODUCTION

The 2016 Kaikoura earthquake provides a reminder of the potential dangers of surface fault ruptures. Fortunately, most ruptures occurred on farm land or sparsely populated areas causing minimal damage. However, for new developments and existing urban areas careful planning is needed to mitigate the hazards presented by surface ruptures. Severe damage may be sustained by structures built directly upon or adjacent to active surface faults. Life-safety is threatened when structures are occupied or form part of critical infrastructure. There are four principal styles of ground deformation associated with surface fault ruptures: distinct rupture planes or scarps, differential settlement and angular distortions, horizontal strains, and tensile cracks (Bray, 2001). Each of these interacts with structures differently and one or all may be present in a particular surface faulting event. Accurate prediction of the spatial and temporal distribution of these deformations allows for improved design of Fault Avoidance Zones (FAZs) and consideration of additional engineering mitigation measures.

2 EXISTING APPROACHES TO FAULT ZONATION

In New Zealand, current hazard mitigation efforts require a fault avoidance zone (FAZ) to be established within which new construction is regulated. The FAZ is delineated using a 20 m setback distance from a recognised active fault or fault zone. In contrast California's Alquist-Priolo Earthquake Fault Zoning Act (AP Act) requires an earthquake fault zone (EFZ) up to 400 m wide to be established around a

potentially hazardous fault. Within the EFZ subsurface investigation is required at each new development site to determine if the site is underlain by an active fault (one which shows evidence of Holocene displacement along a portion of its length). Structures for human occupancy are prohibited from being placed across an active fault and, unless the trench proves otherwise, a 15 m (50 foot) setback distance is enforced around the active fault based on the assumption that active branches are present within this distance (Bryant, 2010). Trench investigations are not required outside an EFZ, making it possible for a structure to be placed over or near an active fault if the fault lies outside of an established EFZ. The limitations of this approach were highlighted by the 1992 Landers Earthquake, in which 45% of surface ruptures occurred outside EFZs (Hart *et al.*, 1993).

New Zealand's Ministry for the Environment (ME) Guidelines define three parameters which can be used to take a risk based approach to hazard assessment—fault recurrence interval, fault complexity, and building importance. Each parameter is divided into several classes. This allows buildings of a low importance class (*e.g.*, farm buildings) to be placed adjacent to faults of a shorter return interval, while prohibiting critical infrastructure, such as hospitals, from being placed adjacent to the same fault. Unlike the AP Act, the avoidance zone (usually 20 m) is established in advance and no further investigation is required.

Little evidence is cited by either the AP Act or ME Guidelines in support of their stated setback distances. Two questions must therefore be addressed. Is this distance adequate to avoid all surface deformation? Can the width of the deformation zone (WDZ) around a surface fault rupture be anticipated accurately? If so, setback distances and EFZs can be designed to be more or less conservative as required, thus reducing the risk of ground deformations occurring outside of established avoidance zones.

The AP Act and ME Guidelines only require active faults to be zoned. The AP Act considers a fault active if it displays evidence of Holocene displacement. The ME Guidelines define six fault classes based on recurrence intervals ranging from <2000 years to ≤125,000 years. This raises several further questions. What is the most appropriate definition of an active fault considering the tectonic setting of New Zealand? How best to assess the activity of a fault given an imperfect geologic record? How best to identify and define a fault in the first place? Should a minor fault with a few centimetres of offset be treated the same as one with several meters of offset?

By not allowing any hazard mitigation measures other than avoidance, the AP Act and ME Guidelines potentially limit the amount of land available for development. Allowing engineering mitigation of minor faults on which there is little displacement or of broad shear zones where discrete ruptures are not expected may be economically beneficial.

3.   GEOLOGICAL CONTROLS ON SURFACE RUPTURE

FAZs should be established using measurable geological criteria to predict the width of the deformation zone surrounding surface fault ruptures, rather than using a pre-determined setback distance. There are six principal factors controlling the general characteristics and rupture path of surface faulting: (1) sense of fault movement (dip-slip or strike-slip); (2) geometry of the fault plane; (3) amount of fault displacement; (4) depth of overlying earth materials; (5) nature of overlying earth materials; (6) definition of the fault (recently developed or established). The effects of these factors are described herein to better understand the nature of surface faulting, aid our ability to predict the distribution of surface deformations, and assess the appropriateness of hazard zoning. The majority of surface fault offset is typically accommodated on a central rupture zone in the order of one to tens of metres width, with secondary off-fault deformations spanning hundreds of metres to over a kilometre (Fenton, 2016). Distributed, off fault deformation may account for a significant portion of the total displacement. Fault ruptures are diverse in nature and may exhibit discrete offsets on fractures or scarps, complex *en echelon* arrays, or broad, distributed shear zones.

Fault geometry is a fundamental factor in controlling surface fault rupture morphology. Each principle fault type (strike-slip, normal, and reverse) creates a different surface expression which needs to be recognised in order to establish effective FAZs.

There is a positive correlation between structural complexity and the magnitude and width of off-fault deformation (Boncio *et al.*, 2012). In the Landers earthquake, off-fault displacement commonly reached over several hundred metres in stepovers, kinks and fault bends (Milliner *et al.*, 2015). The greatest displacements occurred on structurally simple single-stranded sections of the fault. Slip on individual faults decreased in complex zones, as the total displacement was spread over multiple structures. Therefore it would be wise to employ very conservative FAZs around geometric complexities such as stepovers where the surface damage zone is observed to broaden markedly.

Analysis of earthquakes worldwide shows ruptures do not propagate through stepovers or discontinuities >3-4 km and below this distance ruptures are arrested only 40% of the time (Wesnousky, 2008). Furthermore, earthquakes in which fault slip decreases abruptly towards a stepover commonly re-nucleate on adjacent segments (Elliot *et al.*, 2009). Thus, it may be prudent to consider faults that are within <3-4 km of active fault on which displacement decreases abruptly to be zoned as active.

In many faults the damage zone is asymmetric. The hanging wall of dip-slip faults usually experience a wider and more severe deformation zone than the foot wall. Following the 2008 Wenchuan, China earthquake, authorities introduced an asymmetric FAZ around the causative fault which was three times wider on the hanging wall than the foot wall (Yongshuang *et al.*, 2013). Reverse faults typically show less offset at the surface than normal faults of similar displacement in comparable near-surface materials. In addition, surface offset increases with dip (Lade *et al.*, 1984). A shallower dipping fault generally produces a wider rupture zone (Fenton, 2001).

Thick deposits of loose soil (*e.g.*, alluvium) produce wide deformation zones, either as warping, broad *en echelon* arrays or multiple fault strands. In such materials, new surface ruptures may manifest over a wide zone as high angle (with respect to the orientation of the primary fault zone) *en echelon* fractures, whereas low angle fractures are older and more proximal to the pre-existing basement fault (Lin & Nishikawa, 2011). Where surface materials indicate a very broad deformation zone should be expected there are two options; (1) expand the FAZ to encompass all distributed deformation (potentially hundreds of metres); or (2) allow the introduction of engineered mitigation of minor distributed deformations at a certain distance beyond the primary rupture zone.

Fault zones evolve towards geometric simplicity with cumulative slip. Riedel (R) shears form during the initial stages of fault development when resistance to shear is greatest. As the fault zone matures movement on the R shears ceases and central principal displacement shears develop aligned to the general direction of fault movement (Tchalenko, 1970). Strain is localised throughout this process and the zone of active deformation gradually simplifies and narrows such that the older peripheral faults become inactive. Structurally immature faults may manifest ~50-60% of total slip on narrow fault traces whereas structurally mature faults manifest ~85-95% (Dolan & Haravitch, 2014). The missing slip is be accounted for by aseismic creep or distributed off-fault deformation. Borchardt (2010) demonstrated that after 30 fault ruptures, the likelihood of a new rupture developing in a soil that shows no evidence of prior ruptures is negligible. Evidence also suggests that faults in a low-strain setting with long recurrence intervals are prone to complex geometries.

Having an appreciation of the structural maturity of a fault gives an indication of how much off-fault deformation to expect and informs the construction of a displacement-distribution curve. The youngest faults in a fault zone should be identified as these are the most likely to be active and rupture in the future; more distal faults may be inactive.

The general location of surface ruptures is controlled in tectonically active regions by pre-existing fault zones that have either experienced surface faulting in the late Pleistocene or Holocene or are undergoing

active creep (Lin & Nishikawa 2011; Fenton & Kernohan, 2015). Thus, in a general sense, surface ruptures can be expected where they have been observed historically, or for where there is geomorphological evidence of prehistoric ruptures. However, this does not stop a long recurrence interval fault for which there is no existing geomorphic evidence from rupturing to the surface (e.g. 2010 Greendale Fault).

The geological controls on surface rupture morphology described above suggest surface fault ruptures within New Zealand are likely to generate wide, complex patterns of ground deformation. This is because; (1) many faults are structurally complex with oblique strike-slip movements; (2) fault may be covered by loose, uncemented alluvial sediments hundreds of metres thick, moraine, till, fan deposits, or landslide debris; (3) faults may not rupture with characteristic behaviour and have not matured into narrow, linear traces. While primary ruptures can be expected on identifiable pre-existing fault traces, secondary ground deformations for which there is no historic evidence may occur hundreds of metres away. For this reason, applying a 20 m setback distance around the central rupture zone of a fault is not likely to capture the full extent of deformation.

4   CREATING A PREDICTIVE MODEL OF SLIP DISTRIBUTION

The geologic controls on surface rupture and observations from historic events help us to predict the shape of the deformation-distribution curve for an active fault. This should form the basis on which FAZs are established. A fault displacement curve can be used by land-use planners and engineers to completely avoid surface ruptures, allow buildings of lesser or greater importance closer or farther from a fault zone, respectively, or design structures to withstand the expected amount of ground deformation or strain at a particular location.

5   RESPONSE OF STRUCTURES TO SURFACE RUPTURES

Three factors determine the response of structures; (1) total displacement and sense of fault movement; (2) foundation type and surface materials; (3) location of the structure relative to the fault. The distribution of damage to structures is strongly influenced by the distribution of surface ruptures (Zhou, et al., 2010). However, the response of different structures varies significantly. Some may withstand several meters of offset relatively undamaged while others are completely destroyed. In general, structures sustain more damage from vertical displacements than horizontal displacements. Buildings with massive foundations may influence the style and pattern of surface deformation, in some cases diverting strike-slip ruptures that would otherwise run directly beneath them (Kelson *et al*, 2001). For example, in the 1999 Turkey earthquakes, several concrete bunkers with massive foundations in soil diverted ruptures and were able to withstand 3-4 m of horizontal displacement with little or no damage (Bray, 2001). Unreinforced concrete slab foundations perform poorly and generally crack while shallow reinforced foundations tend to tilt or twist without cracking, and may detach from the underlying soil.

Buildings can be engineered to withstand major fault movements and preserve life-safety. Where there is a precedent of building close to or on active faults such as in cities, where developable land is limited, or where a very broad deformation zone is expected, total avoidance may be difficult, costly, or unnecessary. Inevitably, lifelines such as roads and pipelines must also cross active faults. In these circumstances it is worth considering engineering measures which can be used in conjunction with (or instead of) avoidance for non-critical infrastructure (e.g. small residential units) and vulnerable lifeline crossings.

Ductile, compacted, and reinforced earth fills can be used to absorb and diffuse bedrock fault displacements over a wider area. This inhibits the propagation of distinct shears and reduces angular distortion, lateral strains, and differential settlement at the surface (Oettle & Bray, 2013). Stiff, previously ruptured soils should be excavated and replaced with such fills. Fault movements can be spread over a zone approximately 1-2 times the thickness of the fill. Increasing the height, ductility, and

level of reinforcement increases the effectiveness of the fill (Oettle & Bray, 2013). These engineering strategies described above can be used in tandem with FAZs where complete avoidance is not possible or necessary.

6 KEY INPUTS FOR A SURFACE FAULT HAZARD INVESTIGATION

Any surface fault hazard investigation must begin with the identification and characterisation of active faults. Standard geologic maps (Q Map in New Zealand) at scales of 1:250,000 are not adequate for site-specific fault location. Only primary fault traces are marked with no indication of the deformation zone width. When enlarged to the scale required by land planners (<1:10,000), faults are inaccurately portrayed and liable to misinterpretation (ME Guidelines, 2003). Large scale (<1:10,000) geomorphologic mapping must be conducted. Several remote sensing technologies may be employed including LiDAR and aerial and satellite photography as well as field mapping.

LiDAR surveys are particularly advantageous in that they can generate bare-earth topography. This removes the obscuring effects of vegetation and allows the ground below heavily vegetated areas to be imaged. The effects of erosion and local environmental factors should also be recognised. Decades of agriculture are likely to diminish subtle geomorphic indicators of surface faulting. Assessment of the length of a fault beyond that which is observable is justified for faults which are thousands of years old, as the true length of the fault is unlikely to be preserved (Villamor *et al.*, 2012).

Trench investigations are a valuable component of fault hazard studies and should be used to assess the displacement and recurrence interval of fault ruptures. However, the limitations of trenching must be recognised to avoid misinterpretation, and trenches sited in the wrong place or of inadequate length or depth will be of little value. Bonilla and Lienkaemper (1991) found that in 45% of trenches faults appear to die-out upwards and in 30% of trenches faults appear to die-out downwards where other data showed that surface displacement had occurred. Failure to recognise that fault strands often die-out for reasons other than being covered by younger deposits may lead to an underestimation of fault activity (Bonilla and Lienkaemper, 1991).

The spatial and temporal variation in the behaviour of a fault is hard to assess from the single observation point provided by a trench. Care must be taken that the amount of displacement measured in a trench is characteristic of the entire fault. In 1979 there was a small earthquake swarm on two of the faults that ruptured in the 1992 Landers earthquake (Treiman, 2010). The 1979 event generated 0.1 m of slip, yet in 1992 the same area experienced 1-2 m displacement. If a trench were dug in 1980, it may have shown a few centimetres of displacement from the 1979 event, but it may not have been possible to characterize the 1992 event beforehand (Treiman, 2010). Broad shear zones and warping are also unlikely to be appreciated in trench investigations. Wells and Coppersmith (1994) found that for a single event, the average displacement on a fault is half of the maximum displacement. Empirical regressions may assist the estimation of fault rupture parameters that are hard to ascertain by field investigation.

Trenches should extend well beyond the full length of a proposed development. While there may be no evidence for faulting beneath a site, the area may be subject to secondary deformations if a large fault is discovered beyond the site. This may be hard to justify in an area of no known active faults or where there is no geomorphic evidence of faulting, however there are several cases of unknown faults rupturing (e.g. China 2008, Darfield 2010, Kaikoura 2016) which could have been recognised prior in a trench.

It is worth considering the most appropriate definition of an active fault. The six classes defined by the ME Guidelines require rupture intervals to be dated to an accuracy of up to 1500 years; a difficult task given an imperfect geological record and inaccuracies in dating. A simpler approach would be to define fault activity based on evidence for Holocene, Late Quaternary or Quaternary displacements.

7 SUGGESTIONS FOR BEST PRACTICE

Surface fault ruptures are often complex and appear unpredictable. While surface ruptures have occurred on unrecognised faults, there are often subtle, pre-existing geomorphic traces and evidence for prehistoric ruptures in trenches that are only recognized post-evet. A 20 m setback distance may not always be an adequate. Secondary deformations should be expected to span up to hundreds of metres from the central rupture zone. An understanding of the geologic factors that control the style, location, and distribution of surface ruptures allows us to establish wider avoidance zones were necessary. Advances in LiDAR surveys and high resolution aerial photography aid the identification of active fault traces. The response of structures to historic ruptures provides guidance on how to construct surface rupture resistant buildings. This information can be used to establish robust mitigation measures.

New Zealand has a relatively low population density and a large number of active faults. It would be impractical and unnecessary to establish a non-arbitrary avoidance zone for every fault; to do so properly would require extensive geomorphic mapping, detailed trench investigations, all requiring significant capital expenditure. Major active faults in proximity to urban environments are likely to see ongoing civil engineering developments. These faults warrant investigation and the establishment of wide, avoidance zones. This approach would be similar to the AP Act, which requires maps to be published showing potentially hazardous EFZs. The onus would then be on a developer to prove the lack of surface rupture hazard by carrying out the appropriate geological investigations. However, unrecognized faults have ruptured outside of EFZs, so for all critical infrastructure (e.g. hospitals, power stations), even that sited away from known active faults, some specified minimum level of fault investigation would be prudent. For known inland faults away from major urban areas, some minimum level of engineering mitigation within a certain distance (e.g., 1 km) from known active faults would protect life-safety without the need for detailed fault investigations. The current ME Guidelines define narrow fault recurrence intervals that depend on faults having developed characteristic rupture cycles and our ability to date ruptures accurately. How sure can we be that a fault of recurrence interval 2000-3500 years is more likely to rupture than a fault of 3500-5000 years when inaccuracies in dating and an imperfect geologic record are considered? Can we be sure enough to determine the type of building that should be allowed and the potential risk to life we are willing to assume? It may be simpler to simply class faults as Holocene-active or Late Pleistocene-active.

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