Towards the development of design curves for characterising distributed strike-slip surface fault rupture displacement: an example from the 4 September, 2010, Greendale Fault rupture, New Zealand

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ABSTRACT

Surface rupture of the Greendale Fault during the Darfield earthquake extended east-west for ~30 km across gravel-dominated alluvial plains west of Christchurch. It comprised a series of left-stepping traces, and was predominantly dextral strike-slip (maximum 5.3 m). Many linear features (e.g. roads, fences) were displaced by the fault rupture. These were surveyed and provided ideal markers for quantifying the amounts and patterns of surface rupture deformation. Perpendicular to fault strike, dextral displacement was distributed across a ~30 to 300 m wide deformation zone, largely as horizontal flexure. The width of the deformation zone was greatest at step-overs. On average, 50% of the horizontal displacement occurred over 40% of the total width of the deformation zone with offset on discrete shears, where present, accounting for less than about a third of the total displacement. A trench was excavated across the Greendale Fault at a location where there was ~4.8 m of total dextral displacement. Most of this displacement was in the form of horizontal flexure, but there were three discrete shears that each had a maximum of ~0.6 m of dextral offset. The discrete shears were clearly visible in the trench; however, the bulk of the dextral displacement - expressed as horizontal flexure at the ground surface - was not discernible in the trench. These fault displacement documentations have been used to develop provisional design curves for the characterisation of distributed strike-slip surface fault rupture displacement, and have utility with regards to developing mitigation strategies aimed at reducing the damage caused by fault rupture.

1 INTRODUCTION

Ground deformation can contribute significantly to losses in major earthquakes. Compared to areas that experience only strong ground shaking during an earthquake, those areas that also suffer permanent ground deformation (e.g., liquefaction, slope failure, surface fault rupture) sustain greater levels of damage and loss. This relationship was clearly demonstrated during the 2010-2011 Canterbury earthquakes (e.g., NZSEE 2010, 2012; Kaiser et al. 2012). Ultimately, the mitigation of the risks these hazards pose depends on the integrated application of appropriate engineering design and risk-based land-use policy (e.g., Mileti 1999; Bray 2001; Kerr et al. 2003; Saunders & Beban 2012). For such approaches to be successful, however, there is a critical requirement to accurately characterise the ground deformation hazards. In this paper, we develop a framework for doing this for strike-slip surface fault rupture.

The M_w 7.1 Darfield earthquake of 4 September, 2010, had a shallow-focus (~11 km deep), and an epicentre located within ~40 km west of Christchurch (Fig. 1). It was a complex event, involving rupture of multiple fault planes with most of the earthquake's moment release resulting from slip on the previously unrecognized Greendale Fault (e.g., Gledhill et al. 2011; Beavan et al. 2012). Greendale Fault rupture propagated to the ground surface and directly impacted, and damaged, numerous man-made structures such as single-storey buildings, roads and power lines (Van Dissen et al. 2011; Quigley et al. 2012).

In this paper, we quantify Greendale Fault surface rupture deformation: along strike, perpendicular to strike, and in the shallow sub-surface. Using these characterisations, we then place Greendale Fault surface rupture into a wider hazard context that, we hope, will facilitate the future mitigation of surface fault rupture hazard in New Zealand and worldwide.

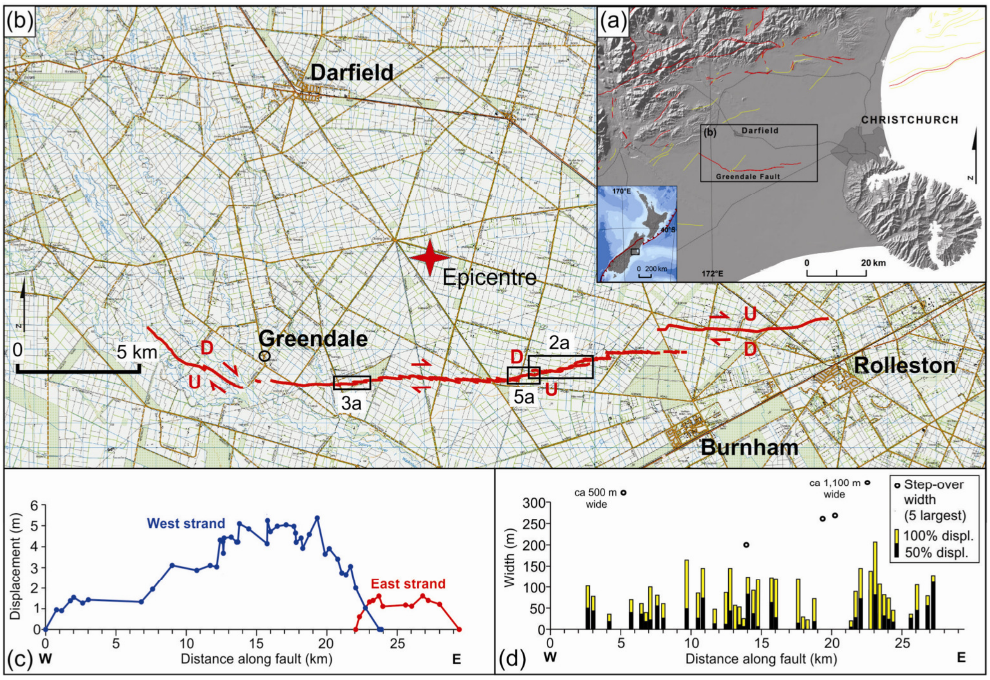

Figure 1: a) Part of the Canterbury region showing locations of the Greendale Fault (including western sub-surface extension) and other active faults and folds (red and yellow lines, respectively) (Forsyth et al. 2008; Barrell et al. 2013). b) Surface trace of the Greendale Fault (Quigley et al. 2012). Also shown are locations of Figures 2a, 3a & 5a, and Darfield earthquake epicentre (red star; Gledhill et al. 2011). c) Net surface fault rupture displacement along the Greendale Fault (after Quigley et al. 2012). d) Width (horizontal distance) measured perpendicular to fault strike over which 50% and 100% of the total dextral surface rupture displacement accumulated, at selected sites, along the Greendale Fault (after Van Dissen et al. 2011).

2 GREENDALE FAULT SURFACE RUPTURE

2.1 Characterisation of surface fault rupture displacement

Ground surface rupture of the Greendale Fault extended for ~30 km across the low-relief pastoral landscape of the Canterbury Plains (Fig. 1), and comprised a distinctive series of en echelon, east-west striking, left-stepping traces (Figs 2a & 3a) (Quigley et al. 2012).

Many linear cultural features such as fences, roads and crop-rows were displaced by the fault rupture (Fig. 2b). Over 100 of these were accurately surveyed, and these provide ideal markers for documenting the amounts and patterns of coseismic surface rupture deformation. Examples of the dextral deformation profiles/histograms obtained at two sites from these surveys are depicted in Figure 2c (profiles for all surveyed sites are available in Litchfield et al. 2013). Surface rupture displacement was predominantly dextral strike-slip, averaging 2.5 m, and reaching a maximum of 5.3 m along the central section of the fault (Fig. 1c) (Quigley et al. 2012). Vertical displacement was typically decimetre-amplitude flexure and bulging, but at several fault bends, vertical displacement reached 1 to 1.5 m. Perpendicular to fault strike, surface rupture displacement was distributed across a ~30 to 300 m wide deformation zone, largely as horizontal flexure (i.e. non-elastic folding about a vertical axis) (Figs. 1d & 2). The width of the surface rupture deformation zone is greatest at step-overs (Figs. 2 & 3a), and damaging ground strains developed within these. The largest step-over is ~1 km wide, and there is a multitude of smaller ones. Push-up "bulges" formed at most of these restraining left-steps (Figs. 2a & 3a), with amplitudes up to ~1 m, but typically less than 0.5 m. On average, 50% of the horizontal displacement occurred over 40% of the total width of the deformation zone (Fig. 1d) with offset on observable discrete shears, where present, typically accounting for less than about a third of the total displacement. Across the paddocks deformed by fault rupture, there is a threshold of surface rupture displacement of ~1 to 1.5 m; greater than this discrete ground cracks and shears occur and form part of the surface rupture deformation zone, and less than this they are rarely present. The distributed nature of Greendale Fault ground surface rupture displacement is undoubtedly, in part, a consequence of the considerable thickness [exceeding 0.5 km in places (Jongens et al. 2012)] of Quaternary gravel deposits that underlie the plains, and that are loose near the ground surface.

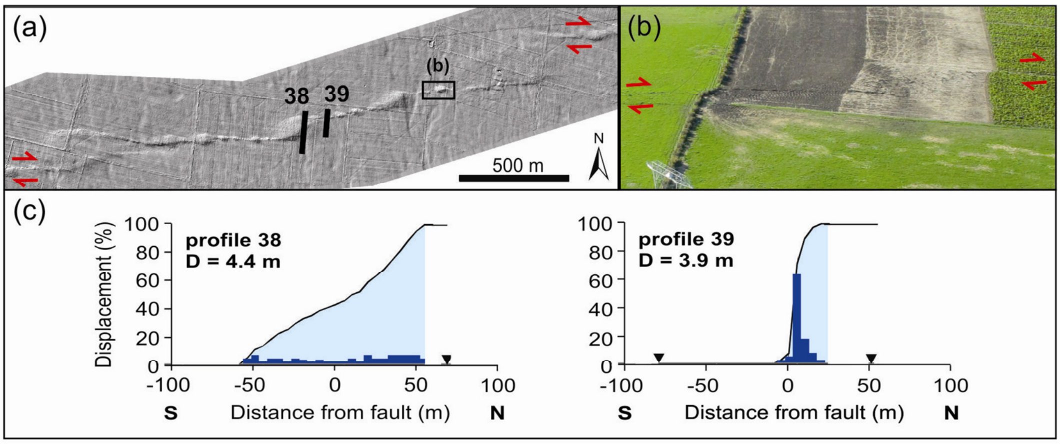

Figure 2: a) LiDAR hillshade digital elevation model of a section of Greendale Fault ground surface rupture. b) Photo showing along-strike variation of surface rupture deformation zone width. The two bare fields are each ~40 m wide, and total dextral displacement is ~4.5 m (after Barrell et al. 2011). c) Plots of cumulative strike-slip surface rupture displacement and histograms of displacement distribution at two representative sites across the Greendale Fault, located in 2a. Surface rupture deformation is widest, and more evenly distributed, at step-overs (profile 38), and narrowest and more spiked where rupture comprises a single trace (profile 39). In these profiles, deformation is projected perpendicular to fault strike, and binned in 5 m increments. D = dextral displacement.

As noted above, the width of the surface rupture deformation zone is greatest at step-overs. To further evaluate this, and its potential influence on the distribution of surface rupture deformation, the 30 dextral deformation profiles that cross the entire fault zone are grouped, and plotted, according to their structural position on the fault trace (Figure 3). In these plots, all deformation profiles are normalised to displacement, and for those profiles crossing a step-over, they are also normalized to step-over width. All three structural groupings (A, B & C of Fig. 3c) show that dextral deformation is predominantly distributed (as opposed to concentrated solely on a small number of discrete shears). Even when the surface rupture deformation zone comprises a single trace (group A of Fig. 3) significant deformation occurs over a width of ~40 m. Across the central part of a step-over (group C), dextral deformation is distributed and equally shared across both sides of the step-over. At the beginnings/endings of a step-over (group B) deformation is, again, distributed, with the dominant side of the step-over (B1 of Fig. 3b) carrying about three times more displacement than the subordinate side (B2 of Fig. 3b).

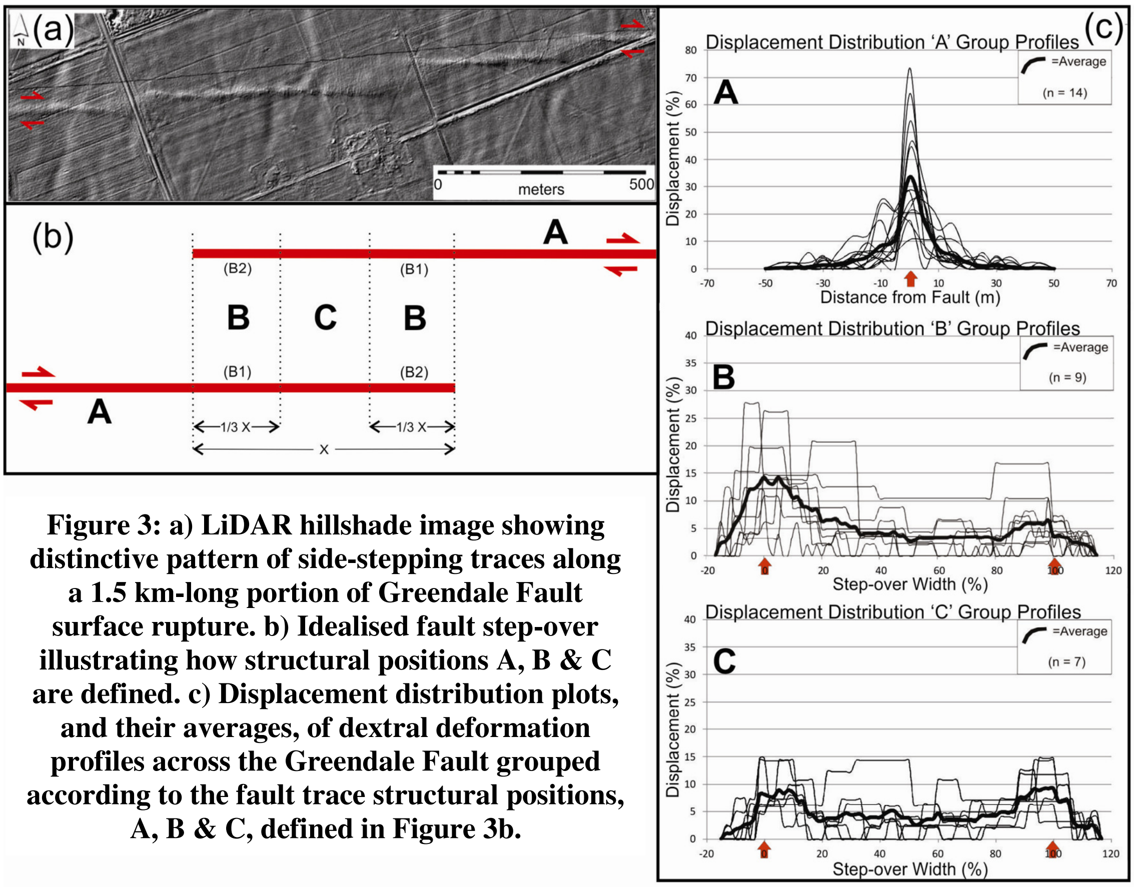

Figure 3: a) LiDAR hillshade image showing distinctive pattern of side-stepping traces along a 1.5 km-long portion of Greendale Fault surface rupture. b) Idealised fault step-over illustrating how structural positions A, B & C are defined. c) Displacement distribution plots, and their averages, of dextral deformation profiles across the Greendale Fault grouped according to the fault trace structural positions, A, B & C, defined in Figure 3b.

Figure 4a plots the Greendale Fault's average displacement distributions for the three structural groupings (A, B & C) defined in Figure 3, along with their corresponding cumulative displacement curves. Figure 4b shows analogous plots for a hypothetical strike-slip case where deformation is entirely discrete. Figure 4c combines the plots shown in Figures 4a & 4b onto a single diagram. Comparable displacement plots are available for two sites along the 1906 rupture of the San Andreas Fault (Bray & Kelson 2006) and 11 sites along the 1999 ruptures of the North Anatolian Fault (Rockwell et al. 2002). Invariably, these strike-slip displacements are less distributed than the Greendale case, more distributed than the hypothetical discrete case, and would fall between the two "bounding" curves of Figure 4c. The potential use of Figure 4c as a provisional design curve for aiding in the improved characterisation, and mitigation, of surface rupture hazard is touched on in Section 3.

2.2 Expression of displacement in the shallow subsurface

To investigate the expression of surface rupture deformation in the shallow subsurface, a trench was excavated adjacent to Highfield Road located along the central, high displacement, section of the Greendale Fault (Figs. 1 & 5). The trench was ~32 m long, 3 m deep, and oriented perpendicular to fault strike (Figs. 5b & 5d). The stratigraphic units exposed in the trench comprised, mainly, fine to coarse gravel, and sandy gravel, interbedded with lenses of sand. The gravel units were loose to slightly compact, and horizontally- to cross-bedded; the clasts within these units were unweathered to slightly weathered, rounded to well rounded, and composed primarily of hard greywacke sandstone.

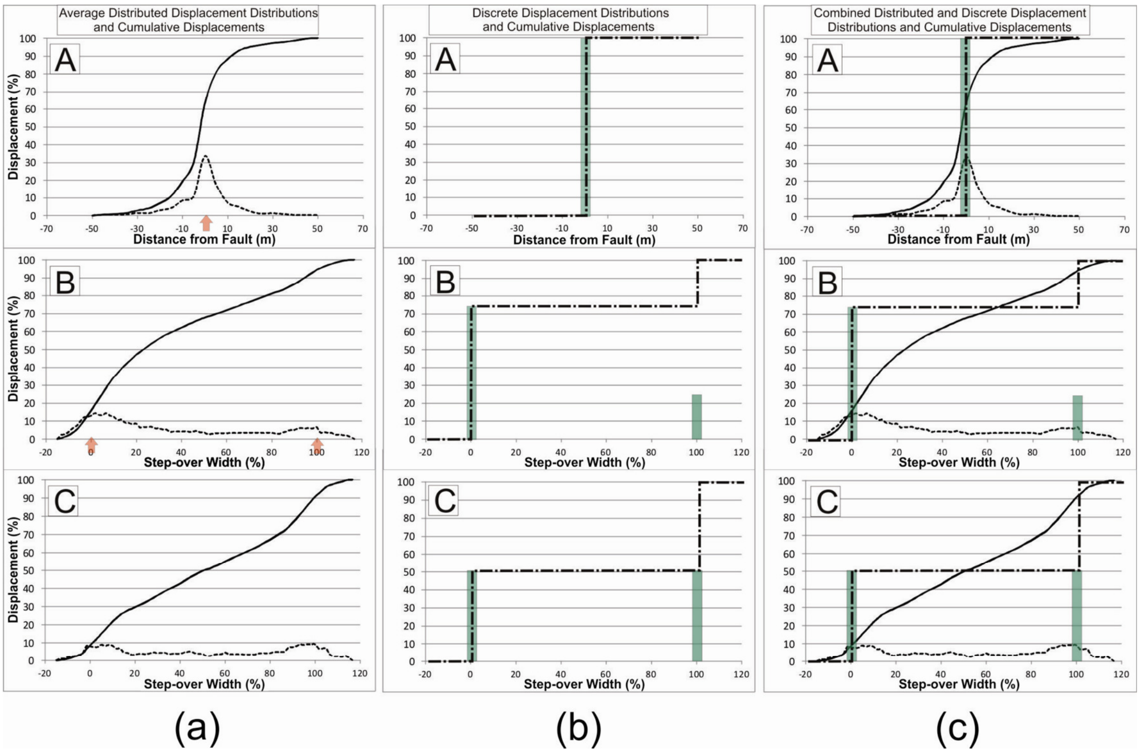

Figure 4: a) Average displacement distributions (dotted lines) and cumulative displacement curves (solid lines) for the Greendale Fault for the three fault trace structural groupings - A, B & C - defined in Figure 3. b) Displacement distributions (green shaded bars) and cumulative displacement curves (dot-dash lines) for a hypothetical case where strike-slip deformation is entirely discrete. Fault trace structural groupings - A, B & C – are as defined in Figure 3. c) Figures 4a & 4b combined, highlighting the differences in slip distribution between the hypothetical end-member discrete displacement example, and the near end-member distributed displacement (Greendale) example.

At Highfield Road, the overall width of the surface rupture deformation zone was ~175 m, and total dextral displacement across this zone was ~4.8 m (Fig. 5c), based on surveying of deformed fence lines, power pole lines, tree lines, and road edges. Total vertical displacement was ~1 m, south side up. The trench was excavated across the conspicuous zone of “ground cracking” visible in Figure 5b. By projecting the position, and extent, of the trench onto the near-by deformation profile (Fig. 5c), we demonstrate that the trench was sited across the portion of the deformation zone with the highest dextral displacement gradient, and we estimate that the trench encompassed/spanned ~60% of the total dextral deformation, or ~2.9 m of the total ~4.8 m. The most prominent features comprising the “ground cracking” zone (i.e., the zone of highest displacement gradient) were three Riedel shears, labelled R1, R2 & R3 in Figure 5. These three shears were the only discrete deformation features exposed that extended from top to bottom of the trench. They were typically expressed as 0.1 to 0.2 m wide bands of sub-vertically imbricated/aligned cobbles, and they each carried about 0.5 to 0.6 m of dextral displacement. Of the total dextral displacement encompassed by the trench, ~2.9 m, discrete displacement accounted for 1.5 to 1.8 m of this, or about 50 to 60%. The remaining 40 to 50% of dextral deformation encompasses by the trench - expressed as horizontal flexure at the ground surface - was undiscernible in the gravels exposed in the trench. Across the entire surface fault rupture deformation zone at Highfield Road, discrete dextral displacement accounted for only about a third of the total dextral deformation.

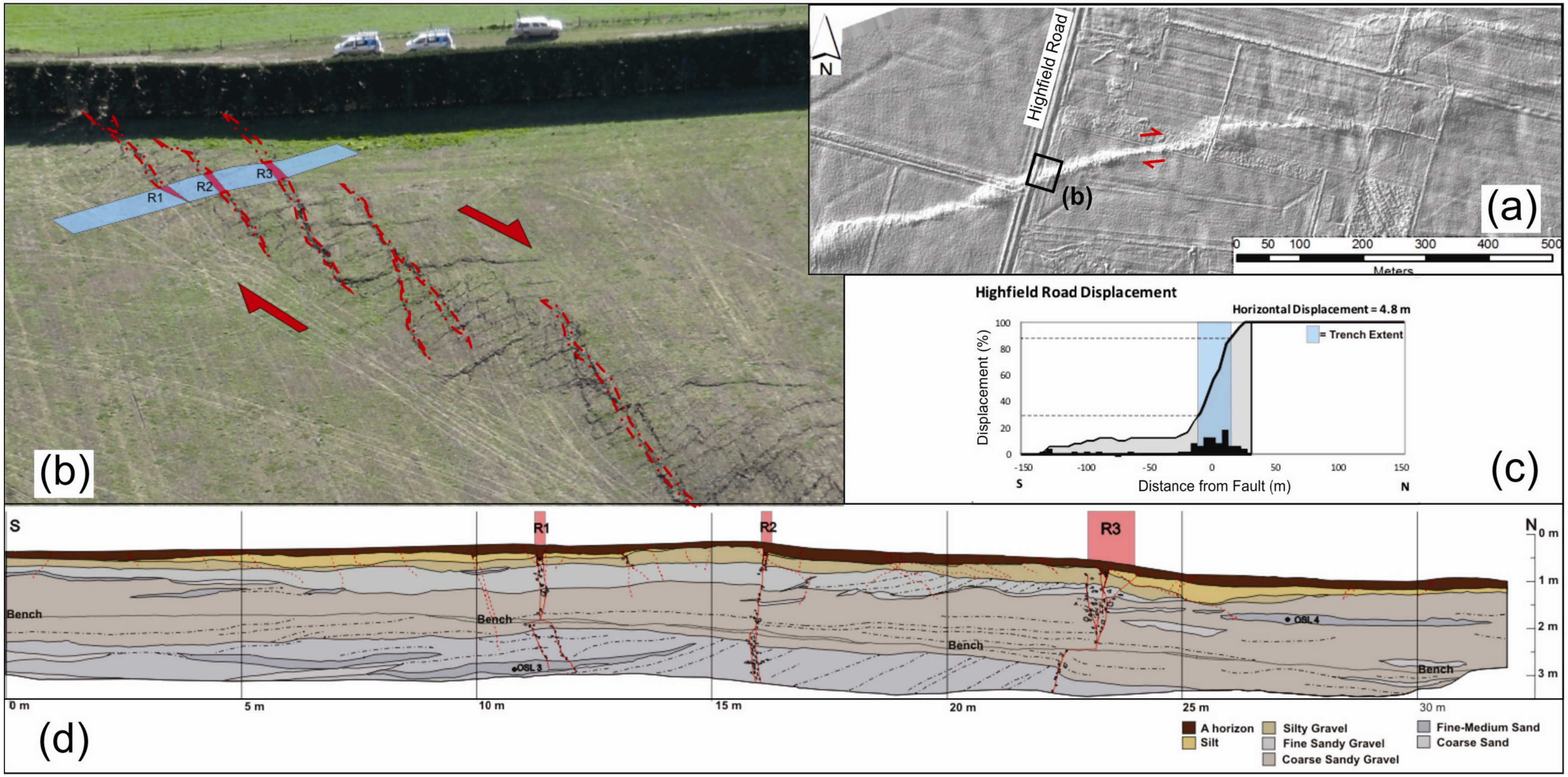

Figure 5: a) LiDAR hillshade image of the Greendale Fault ground surface rupture in the Highfield Road area. b) Photo of the Greendale Fault surface rupture deformation in the Highfield Road area showing location of trench (blue shading) and prominent Riedel shears (red dashed lines). The cars in background are parked along Highfield Road. c) Plot of cumulative dextral surface rupture displacement and histogram of displacement distribution across the Greendale Fault at Highfield Road. Plots are perpendicular to fault strike, and blue shading depicts location and extent of trench. d) Log of the west wall of Highfield Road trench.

3 DISCUSSION & CONCLUSIONS

The Canterbury earthquake sequence is the most costly natural hazard event to impact New Zealand. Estimated losses are upwards of $40 billion (equivalent to ~29% real GDP). This level of loss is debilitatingly large and illustrates a clear economic and societal need in New Zealand to improve earthquake resilience. For this to be achieved, progress on a number of related fronts is needed; the most important being improved levels of damage limitation and post-event functionality in the built environment, and greater sustainability in land-use. Related to this is the realisation that as performance expectations increase for a structure (e.g., building / lifeline), then increased characterisations of the hazards that may impact that structure are also required so that the risks posed by those hazards can be more fully accommodated/mitigated in the design, construction and siting of the structure.

We consider that the displacement distribution curves presented in Figure 4c can be used, following the indicative steps outlined below, to assist improved characterisation of strike-slip surface fault rupture hazard. In general terms, this approach is similar to that described in Kelson et al. (2004).

1) Determine the amount of surface rupture displacement at the site of interest using, for example, a combination of site specific investigations and empirical ground surface displacement regressions such as Well & Coppersmith (1994) and Wesnousky (2008).
2) Establish the location of the site in relation to fault trace structural position (i.e., is the site on, or across, the middle of a step-over, the beginning/end of a step-over, or a single trace). If the site is on, or across, a step-over, determine the width of the step-over.
3) Determine if the site is likely to experience distributed (Greendale-like) displacement, discrete displacement, or something in between. This is potentially the most subjective step. Settings that would tend to favour discrete displacement include, but are not limited to, those where bedrock is at or very near the ground surface, and the fault has a short recurrence interval and large total offset. Conversely, settings favouring distributed deformation would include those where there is a thick sequence of weak/loose material above bedrock, and the fault has a long recurrence interval and small total offset (i.e., is geologically immature).
4) Use Figure 4c and the determinations of items 1-3 above to construct displacement distribution and cumulative displacement curves for the site of interest. Note that Figure 4c applies only to strike-slip ruptures, and is based on data where the step-overs are exclusively restraining/contractional. The curves are untested in releasing/extensional step-over settings. Also, these curves do not account for vertical displacement nor, in a distributed displacement setting, do they explicitly constrain the location and amount of any discrete displacement that may occur. To the extent that these aspects may be of relevance to the engineering / planning project at hand, they will need to be assessed separately.

Improved parameterisation of surface fault rupture hazard - especially when combined with the rupture resilient design concepts presented in Bray (2001) and Bray & Kelson (2006), and the land-use planning guidance provided in Kerr et al. (2003) - will facilitate development of mitigation strategies aimed at reducing the damage caused by surface fault rupture, and improving the post-event functionality of structures that may be impacted by fault rupture.

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