Proceedings of the Ninth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Society
14-16 April, 2011, Auckland, New Zealand

Surface rupture displacement on the Greendale Fault during the M_w 7.1 Darfield (Canterbury) earthquake, New Zealand, and its impact on man-made structures

R. Van Dissen[1], D. Barrell[1], N. Litchfield[1], P. Villamor[1], M. Quigley[2], A. King[1], K. Furlong[3], J. Begg[1], D. Townsend[1], H. Mackenzie[2], T. Stahl[2], D. Noble[2], B. Duffy[2], E. Bilderback[2], J. Claridge[2], A. Klahn[2], R. Jongens[1], S. Cox[1], R. Langridge[1], W. Ries[1], R. Dhakal[2], A. Smith[2], S. Hornblow[2], R. Nicol[2], K. Pedley[2], H. Henham[2], R. Hunter[2], A. Zajac[1], T. Mote[4]

[1]GNS Science, NZ; [2]University of Canterbury, NZ; [3]Penn State University, USA; [4]Arup, Australia

ABSTRACT: Surface rupture of the previously unrecognised Greendale Fault extended west-east for ~30 km across alluvial plains west of Christchurch, New Zealand, during the M_w 7.1 Darfield (Canterbury) earthquake of September 2010. Surface rupture displacement was predominantly dextral strike-slip, averaging ~2.5 m, with maxima of ~5 m. Vertical displacement was generally less than 0.75 m. The surface rupture deformation zone ranged in width from ~30 to 300 m, and comprised discrete shears, localised bulges and, primarily, horizontal dextral flexure. About a dozen buildings, mainly single-storey houses and farm sheds, were affected by surface rupture, but none collapsed, largely because most of the buildings were relatively flexible and resilient timber-framed structures and also because deformation was distributed over a relatively wide zone. There were, however, notable differences in the respective performances of the buildings. Houses with only lightly-reinforced concrete slab foundations suffered moderate to severe structural and non-structural damage. Three other buildings performed more favourably: one had a robust concrete slab foundation, another had a shallow-seated pile foundation that isolated ground deformation from the superstructure, and the third had a structural system that enabled the house to tilt and rotate as a rigid body. Roads, power lines, underground pipes, and fences were also deformed by surface fault rupture and suffered damage commensurate with the type of feature, its orientation to the fault, and the amount, sense and width of surface rupture deformation.

1 INTRODUCTION

The M_w 7.1 Darfield (Canterbury) earthquake of 4 September, 2010 (NZ date) had a shallow-focus (~11 km deep), and an epicentre located within ~40 km west of Christchurch, New Zealand's second largest city (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 unknown Greendale Fault (Beavan *et al*. 2010; Gledhill *et al*. 2010, 2011; Holden *et al*. 2011). Greendale Fault rupture propagated to the ground surface and extended east-west for ~30 km (Quigley *et al*. 2010). Surface rupture was mainly dextral strike-slip, expressed on left-stepping, en echelon traces across the low relief and well-maintained pastoral landscape of the Canterbury Plains (Figs 1 & 2). This afforded an ideal environment for characterising even the most subtle of surface fault rupture deformation. Greendale Fault surface rupture also directly impacted and damaged numerous man-made structures such as single-storey buildings, roads and power lines. In this paper we present a summary of the characteristics of Greendale Fault surface rupture deformation, and the impacts this deformation had on man-made structures. In doing so we hope to make a useful contribution to the body of literature documenting the effects of surface fault rupture on man-made structures (e.g. Bray 2001, 2009a, 2009b; Bray & Kelson 2006; Honegger *et al*. 2004; Kelson *et al*. 2001a, 2001b; Lazarte *et al*. 1994;

Lettis *et al*. 2000; Murbach *et al*. 1999; Niccum *et al*. 1976; Ulusay *et al*. 2001), and providing information relevant to developing strategies aimed at mitigating damage caused by surface fault rupture.

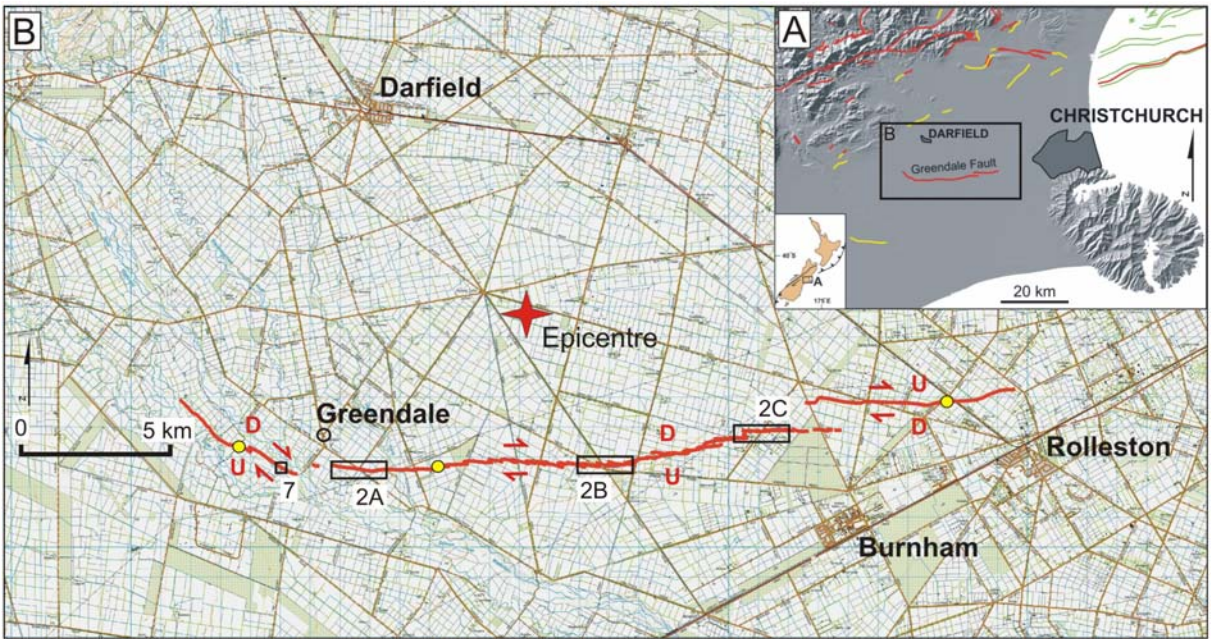

Figure 1. A) Digital Elevation Model (DEM) of the Christchurch area of the Canterbury region showing locations of the Greendale Fault and other tectonically active structures. Red lines are active faults, and yellow and green lines are, respectively, on-land and off-shore active folds (combined data from Forsyth *et al*. (2008) and GNS Active Faults Database, http://data.gns.cri.nz/af/). B) Mapped surface trace of the Greendale Fault (Quigley *et al*. 2010). Red arrows indicate relative sense of lateral displacement, while vertical displacement is denoted by red U = up and D = down. Also shown are locations of Figures 2A-C & 7, Darfield earthquake epicentre (red star; Gledhill *et al*. 2010, 2011), and buildings damaged by surface fault rupture (yellow dots) that are neither encompassed by Figure 2 nor depicted elsewhere in this paper due to space limitations.

2 GREENDALE FAULT SURFACE RUPTURE DISPLACEMENT AND EXPRESSION

A variety of methods were used to map and characterise the Greendale Fault surface rupture (Quigley *et al*. 2010), including tape and compass, GPS surveys, aerial photography, and airborne LiDAR (Fig. 2). The location of the fault rupture in an agricultural landscape with abundant linear features such as roads, fences, power lines, and crop rows provided a wealth of fault displacement markers that allowed the amount and style of displacement to be measured with high precision at more than 100 localities along the entire length of surface rupture.

The zone of identified surface rupture extends for about 30 km from ~4 km west of the hamlet of Greendale (from which the fault gets its name) to an eastern tip ~2 km north of the town of Rolleston (Fig. 1). The gross morphology of the surface rupture is that of an en echelon series of east-west striking, left-stepping surface traces (Figs 1 & 2). 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, with amplitudes up to ~1 m, but typically less than 0.5 m (Figs 2B & 2C).

Displacement along the full length of surface rupture averages ~2.5 m (predominantly dextral), and is distributed roughly symmetrically along the fault. There is an ~8 km long central section of fault trace where net displacement exceeds 4 m, with maxima of ~5 m, and there are ~6 km long sections at either end of the fault where net displacement is less than ~1.5 m. Over the reach of the fault where displacement exceeds the average, the deformation zone comprises east-southeast striking Riedel fractures with right-lateral displacements, southeast striking extensional fractures, south-southeast to south striking Riedel fractures with left-lateral displacements, northeast striking thrusts, horizontal dextral flexure, and decimetre-amplitude vertical flexure and bulging.

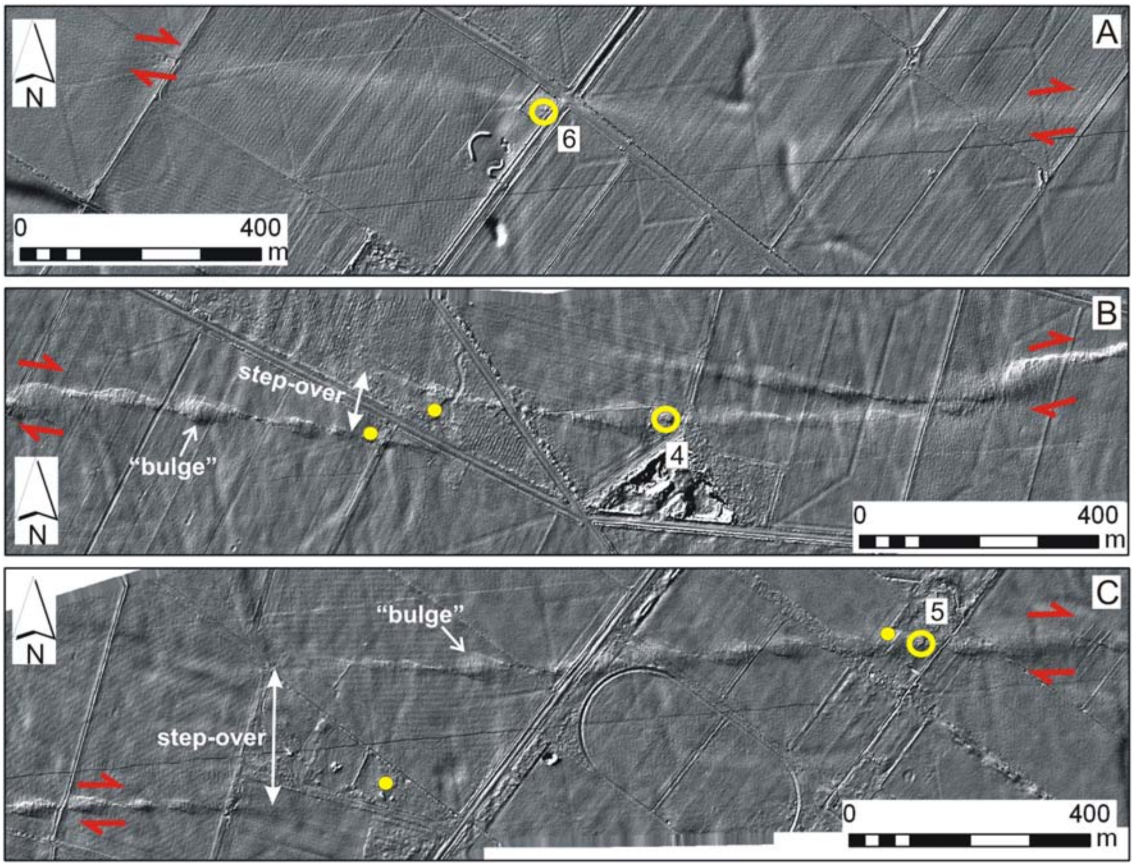

Figure 2. LiDAR hillshade DEMs (illuminated from the NW) of three ~1.8 km long sections of the Greendale Fault (see Figure 1 for locations), showing characteristic left-stepping en echelon rupture pattern (especially evident in B & C), and dextral offset of roads, fences, irrigation channels, hedges and crop rows. Red arrows straddle the surface fault rupture and show the sense of lateral displacement. Representative examples of fault step-overs and push-up "bulges" are identified in B & C. Open yellow circles show the locations of buildings damaged by surface fault rupture that are depicted and discussed in Figures 4-6. Small yellow dots show the locations of other buildings damaged by surface rupture deformation that are not discussed in this paper. The general amount of net surface rupture displacement in A, B, and C is, respectively, 1.5 to 2.5 m (horizontal to vertical ratio ~3:1, south side up), 4 to 5 m (predominantly dextral), and 4 to 2.5 m (predominantly dextral).

Perpendicular to the strike of the Greendale Fault, surface rupture displacement is distributed across a ~30 to 300 m wide deformation zone (Fig. 3), largely as horizontal flexure. The width of the surface rupture deformation zone is greatest at step-overs, and damaging ground strains developed within these. On average, 50% of the horizontal displacement occurs over 40% of the total width of the deformation zone with offset on discrete shears, where present, typically accounting for less than 25% of the total displacement. Across the paddocks deformed by fault rupture, there is a threshold of surface rupture displacement of ~1.5 m, or greater, where discrete ground cracks and shears occur and form part of the surface rupture deformation zone, and less than this where they are rarely present. The distributed nature of Greendale Fault surface rupture displacement undoubtedly reflects a considerable thickness of poorly consolidated alluvial gravel deposits underlying the plains.

Vertical throw across the full width of the surface rupture deformation zone is typically less than 0.75 m. Generally the south side is up, though the eastern ~6 km of the trace is north side up. Vertical displacement increases locally to ~1 to 1.5 m at significant restraining and releasing bends.

3 EFFECTS OF SURFACE RUPTURE ON MAN-MADE STRUCTURES

About a dozen buildings, typically single-storey timber-framed houses and farm sheds with light-weight roofs, lay either wholly, or partially, within the Greendale Fault surface rupture deformation zone (Figs 1, 2, 4-7). None of these buildings collapsed, even those with more than 0.5 m of discrete

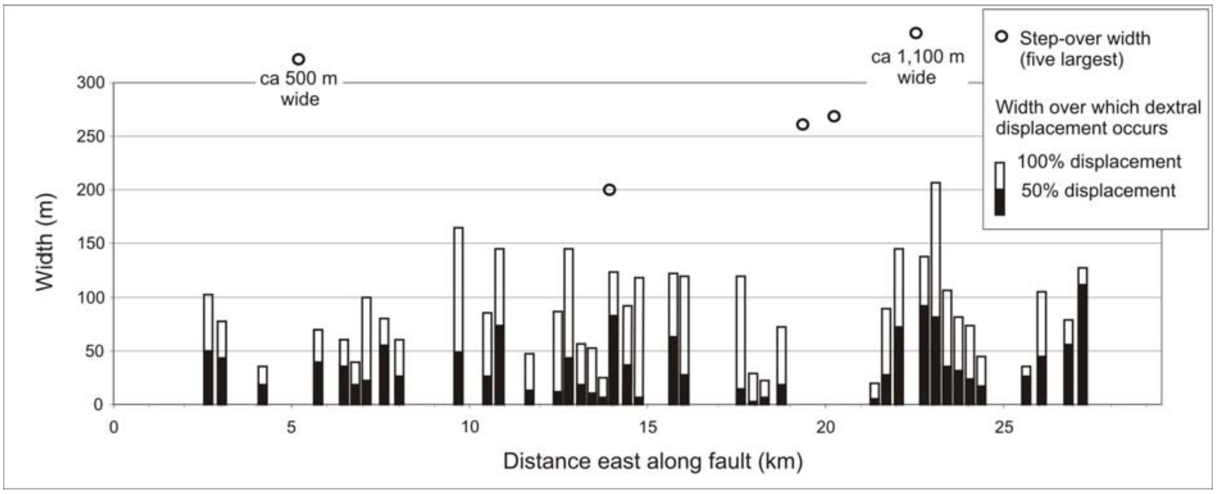

Figure 3. Width (horizontal distance) measured perpendicular to fault strike over which it takes to accumulate 50% and 100% of the total dextral surface rupture displacement at 40 sites along the Greendale Fault. 50% widths are centred over the portion of the deformation zone that exhibits the greatest amount of displacement. The average width of the surface rupture deformation zone is about 80 to 90 m, excluding the largest step-overs. It is relevant to note that the true width of deformation, as documented in the field through detailed surveys of deformed fences and the like, is usually several tens of metres wider than the width of deformation evident in hillshade LiDAR images as processed and depicted in Figure 2, and can be over 100 m wider. For example, the eastern ~7 km of surface rupture, across which there is as much as ~1.5 m of dextral and ~0.5 m of vertical distributed deformation, is not visible in hillshade LiDAR images similar to those depicted in Figure 2.

shear extending through/under them (Figs 4 & 5), but all were more damaged than comparable structures immediately outside the zone of surface rupture deformation. Some of the buildings most damaged by fault rupture are scheduled for demolition. From a life-safety standpoint, all these buildings performed satisfactorily, but with regard to post-event functionality, there are notable differences. The houses with lightly-reinforced concrete slab foundations (often also brick-clad) suffered moderate to severe structural and non-structural damage. Three other buildings exhibited more favourable performance and will be potentially more straightforward to reinstate. One had a reportedly well-reinforced concrete slab foundation (Fig. 6). Another had a shallow-seated pile foundation that fortuitously isolated a significant amount of ground deformation from the timber-framed, metal-clad superstructure (Fig. 5). The third, despite having steel piles set in concrete, had a steel and plywood structural system that was exceptionally robust and allowed the house to tilt and rotate as a rigid body (Fig. 7).

Characterising the hazards associated with surface fault rupture, and developing design strategies to mitigate those hazards have been the focus of a number of publications by J.D. Bray (e.g. Bray 2001, 2009a, 2009b; Bray & Kelson 2006). In these, he consistently highlights four principal means for addressing surface fault rupture hazard: i, land use planning; ii, engineering geology; iii, geotechnical engineering; iv, structural engineering. Depending on fault rupture characteristics and site conditions, he advocates a number of potentially effective design measures that include: establishing non-arbitrary setback distances; constructing earth fills to partially absorb and distribute underlying rupture; isolating foundations from underlying ground movement (e.g. through the use of slip layers); and designing strong, ductile foundations that resist imposed earth pressures. Observations of building response to the Greendale Fault surface rupture are supportive of Bray's recommendations. Those houses with lightly-reinforced concrete slab foundations (e.g. Fig. 4) would have benefited from having foundations that were stronger and more ductile, and/or able to isolate underlying fault rupture from the overlying house. Buildings less damaged by surface rupture deformation were those that had foundations that were strong enough to resist imposed strains (Fig. 6), or isolated ground deformation from the superstructure (Fig. 5). From the perspective of post-event reinstatement, the building that performed best is depicted in Figure 7. It had the capacity to tilt and rotate as a rigid body, suffering very little internal deformation, and will be relatively straightforward to re-level. For buildings that could be subjected to tilting due to surface rupture deformation, design measures that not only limit damage, but also facilitate re-leveling are advantageous and, as this house illustrates, achievable.

Figure 4. Timber-framed, brick-clad house with concrete slab foundation (at most only lightly-reinforced) and light-weight roof that is located within a ~150 m wide deformation zone accommodating 4 to 5 m of dextral displacement. The house is badly damaged by distributed deformation, and ~0.5 m of discrete strike-slip rupture (red arrows) that enters the house through the front door (B), passes through the house's foundation (including living room), and exits through the back door (D). Photos: A by Richard Cosgrove looking S; B by Hayden Mackenzie looking WNW; C by Hayden Mackenzie looking SSW; D by Dougal Townsend looking ESE.

Figure 5. Timber-framed farm shed that is located within a 25 to 50 m wide deformation zone comprising both discrete shears (red arrows) and distributed deformation, and accommodating ~2.7 m of net slip (predominantly strike-slip - note dextral offset of irrigation channel in right-hand side of A). The farm shed is made up of two parts, a larger metal-clad structure with a timber floor that is founded on shallow seated ~700 mm high concrete piles (D), and a smaller lean-to structure attached to the side (A & C). The lean-to is a pole building (part metal-clad and part wood-clad) with an unreinforced concrete floor. The response of the two different construction styles to surface fault rupture was noticeably different. The support poles of the lean-to are set into the ground. Dextral fault rupture under the lean-to led to lateral displacement of the support poles on either side of the rupture, and significant distortion of the walls and roof (C). In contrast, surface rupture deformation under the larger piled structure was, in large measure, isolated from the superstructure by rotation of the shallow seated piles. The timber flooring and framing, and metal cladding proved a resilient structural system that limited internal distortion. It would be a relatively straightforward process to re-level and reinstate this portion of the building. Photos: A by Richard Cosgrove looking NE; B by Dougal Townsend looking W; C by Dougal Townsend looking E; D by Russ Van Dissen looking SW.

Figure 6. A) Light-industrial building with a reportedly well-reinforced concrete slab foundation is tilted and rotated, but relatively undamaged, by ~1.7 m dextral and < 1 m vertical (south side up) displacement distributed across a ~100 m wide deformation zone. Red arrows denote location, strike and sense of lateral displacement of the surface rupture deformation zone. Photo by Richard Jongens looking NE. B) Fence line adjacent to site crosses the surface rupture deformation zone and records the amount, width, and distributed style of fault displacement here (camera location for B is shown by black "f" in A). Photo by Russ Van Dissen looking SW. C & D) Long axis of building is oriented ~55° counter-clockwise to the general strike of the fault rupture. Distributed displacement imposed tensile ground strains across the site with an orientation roughly sub-parallel to the building's long axis. The foundation of the building was robust enough to resist these strains (i.e. no cracking of the foundation was evident) and, instead, the soil pulled away from either end of the building's foundation (yellow "t" in C & D). Photos C & D by Russ Van Dissen looking NW.

In 2003, the Ministry for the Environment (MfE), New Zealand, published best practice guidelines for mitigating surface fault rupture hazard (Kerr *et al*. 2004, MfE Active Fault Guidelines. Also see Van Dissen *et al*. 2006). Key rupture hazard parameters in the MfE Active Fault Guidelines are Fault Complexity along with Building Importance and surface fault rupture recurrence interval. For a given displacement, the amount of deformation at a specific locality is less within a distributed rupture zone where displacement is spread out, than it is within a narrow zone where rupture is concentrated. The relative fault rupture hazard is therefore less within a zone of distributed deformation than it is within a narrow concentrated zone. As discussed above, surface rupture displacement on the Greendale Fault was typically distributed across a relatively wide zone of deformation. Buildings located within this distributed zone of deformation were subjected to only a portion of the fault's total surface rupture displacement, and no building within this zone collapsed. This provides a clear example of the appropriateness of the MfE's *Distributed* Fault Complexity parameter, at least for Building Importance Category 2a buildings (i.e. residential structures), and with respect to life-safety.

Roads, power lines, underground water pipes, fences, and a railway line were also deformed by Greendale Fault rupture, with damage commensurate with the type of feature, its orientation to the fault, and the amount, sense and width of surface rupture deformation. Of particular note, linear features that spanned all, or part, of the surface rupture deformation zone, as well as being displaced across the fault, were also subjected to lengthening, or shortening, depending on their orientations with respect to the dextral shear direction (e.g. Bray & Kelson 2006; Taylor & Cluff 1977).

Figure 7. A) Light-gauge steel-framed, plywood- and weatherboard-clad house with steel pile foundation, steel I-beam bearers, steel joists and plywood flooring that is tilted, and rotated, but only slightly damaged by ~1 m of distributed vertical and dextral fault rupture spread over several tens of metres width. Photo by Russ Van Dissen looking E. B) Close-up of pile, bearer and deformed bolted connection. Photo by Russ Van Dissen looking WNW. Despite this house being essentially "locked" into the ground (piles are concreted to ~1 m depth into the ground), it suffered only slight damage because surface rupture deformation was distributed and relatively evenly spread across the site, and because the structural system was strong and stiff enough to tilt and rotate as a rigid body. Given this structure's resilient, and somewhat uncommon, construction style, it should be a relatively straightforward process to re-level and reinstate the house. This building was subjected to both surface fault rupture and epicentral-strength strong ground shaking, and performed in a fashion that not only greatly exceeded life-safety objectives, but will also greatly facilitate post-event reinstatement. However, if the building had been subjected to greater amounts of deformation, especially discrete displacement, the pile foundation may have been able to transfer enough deformation into the superstructure to damage it. Design modifications to potentially mitigate this, yet still retain the building's noteworthy resilience, could be to: i) use piles specifically designed to yield during surface fault rupture, and/or ii) use two sets of bearers with one set attached to the piles and oriented parallel to the strike of the fault, and another orthogonal set on top, onto which the floor joists are attached. With due geological and engineering consideration both these options could conceivably be employed to successfully isolate ground rupture from the superstructure and still retain the advantageous ease of re-levelling qualities of this type of construction.

4 CONCLUSIONS

During the M_w 7.1 Darfield (Canterbury) earthquake, surface rupture of the previously unrecognised Greendale Fault extended west-east for ~30 km across gravel-dominated alluvial plains west of Christchurch. Surface rupture displacement was predominantly dextral strike-slip with maxima of ~5 m, and an average of ~2.5 m. Displacement was distributed over a ~30 to 300 m wide zone, and accommodated mainly by horizontal dextral flexure. Vertical deformation was typically decimetre-amplitude flexure and bulging, but at several fault bends, vertical displacement reached 1 to 1.5 m. About a dozen single-storey buildings were directly impacted by Greendale Fault surface rupture. None of these buildings collapsed, and several performed in a fashion far exceeding life-safety objectives. These provide examples of construction styles that could be employed to potentially mitigate surface fault rupture hazard and facilitate post-event reinstatement. The Darfield earthquake was the first New Zealand surface rupture earthquake since publication of the MfE Active Fault Guidelines. The distributed nature of surface rupture deformation along the Greendale Fault, and the fact that no buildings located within the deformation zone collapsed, highlights the value of the *Distributed* Fault Complexity parameter of the MfE Active Fault Guidelines.

5 REFERENCES

Bray, J.D. 2009a. Earthquake surface rupture design considerations. *In proceedings,* 6th International Conference on Urban Earthquake Engineering, Tokyo Institute of Technology, Tokyo, Japan: 37-45.

Bray, J.D. 2009b. Designing buildings to accommodate earthquake surface fault rupture. *In proceedings,* ATC and SEI Conference on Improving the Seismic Performance of Existing Buildings and Other Structures, San Francisco, USA: 1269-1280.

Bray, J.D. 2001. Developing mitigation measures for the hazards associated with earthquake surface fault rupture. *In proceedings,* A Workshop on Seismic Fault-Induced Failures – Possible Remedies for Damage to Urban Facilities, Japan Society for the Promotion of Science, Tokyo, Japan: 55-79.

Bray, J.D., Kelson, K.I. 2006. Observations of surface fault rupture from the 1906 earthquake in the context of current practice. *Earthquake Spectra* 22(S2): S69-S89.

Beavan, J., Samsonov, S., Motagh, M., Wallace, L., Ellis, S., Palmer, N. 2010. The M_w 7.1 Darfield (Canterbury) earthquake: geodetic observations and preliminary source model. *Bulletin of the New Zealand Society for Earthquake Engineering* 43(4): 228-235.

Forsyth, P.J., Barrell, D.J.A., Jongens, R. 2008. Geology of the Christchurch area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 16. 1 sheet +67 p. Lower Hutt, New Zealand. GNS Science.

Gledhill, K., Ristau, J., Reyners, M., Fry, B., Holden, C. 2010. The Darfield (Canterbury) M_w 7.1 earthquake of September 2010: preliminary seismological report. *Bulletin of the New Zealand Society for Earthquake Engineering* 43(4): 215-221.

Gledhill, K., Ristau, J., Reyners, M., Fry, B., Holden, C. 2011. The Darfield (Canterbury, New Zealand) M_w 7.1 earthquake of September 2010: a preliminary seismological report. *Seismological Research Letters*: in press.

Holden, C., Beavan, J., Fry, B., Ristau, J., Reyners, M., Villamor, P., Quigley, M., Van Dissen, R. 2011. Preliminary source model investigations of the M_w 7.1 Darfield earthquake. *In proceedings,* 9th Pacific Conference on Earthquake Engineering, New Zealand Society for Earthquake Engineering, Auckland, NZ: this volume.

Honegger, D.G., Nyman, D.J., Johnson, E.R., Cluff, L.S., Sorensen, S.P. 2004. Trans-Alaska pipeline system performance in the 2002 Denali fault, Alaska, earthquake. *Earthquake Spectra* 20(3): 707-738.

Kelson, K.I., Kang, K.-H., Page, W.D., Lee, C.-T., Cluff, L.S. 2001a. Representative styles of deformation along the Chelungpu fault from the 1999 Chi-Chi (Taiwan) earthquake: geomorphic characteristics and responses of man-made structures. *Bulletin of the Seismological Society of America* 91: 930-952.

Kelson, K.I., Bray, J., Cluff, L., Harder, L., Kieffer, S., Lettis, W., Page, W., Perkins, W., Rix, G., Roblee, C., Sitar, N., Wells, D., Wright, R., Yashinsky, M. 2001b. Fault-related surface deformation. *Earthquake Spectra* 17 (supplement A: Chi-Chi, Taiwan, Earthquake of September 21, 1999, reconnaissance report): 19-36.

Kerr, J., Nathan, S., Van Dissen, R., Webb, P., Brunsdon, D., King, A. 2004. Planning for development of land on or close to active faults: a guideline to assist resource management planners in New Zealand. Published by the Ministry for the Environment, *ME numbers 483 & 565*.

Lazarte, C.A., Bray, J.D., Johnson, A.M., Lemmer, R.E. 1994. Surface breakage of the 1992 Landers earthquake and its effect on structures. *Bulletin of the Seismological Society of America* 84: 547-561.

Lettis, W., Bachhuber, J., Witter, R., Barka, A., Bray, J., Page, W., Swan, F., Witter, R., Altunel, E., Bardet, J.-P., Boulanger, R., Brankman, C., Cakir, Z., Christofferson, S., Cluf, L., Dawson, T., Fumal, T., Güneysu, A.C., Hengesh, J., Kaya, A., Langridge, R., Raathje, E., Stenner, H. 2000. Surface fault rupture. *Earthquake Spectra* 16 (supplement A: Kocaeli, Turkey, earthquake of August 17, 1999, reconnaissance report): 11-53.

Murbach, D., Rockwell, T.K., Bray, J.D. 1999. The relationship of foundation deformation to surface and near-surface faulting resulting from the 1992 Landers earthquake. *Earthquake Spectra* 15: 121-144.

Niccum, M.R., Cluff, L.S., Chamorro, F., Wyllie, L. 1976. Banco Central de Nicaragua: a case history of a high-rise building that survived surface fault rupture. *Engineering Geology and Soils Engineering Symposium No. 4*, Humphrey, C.B. (ed), Transportation Department, Division of Highways, Boise, Idaho: 133-144.

Quigley, M., Van Dissen, R., Villamor, P., Litchfield, N., Barrell, D., Furlong, K., Stahl, T., Duffy, B., Bilderback, E., Noble, D., Townsend, D., Begg, J., Jongens, R., Ries, W., Claridge, J., Klahn, A., Mackenzie, H., Smith, A., Hornblow, S., Nicol, R., Cox, S., Langridge, R., Pedley, K. 2010. Surface rupture of the Greendale Fault during the M_w 7.1 Darfield (Canterbury) earthquake, New Zealand: initial findings. *Bulletin of the New Zealand Society for Earthquake Engineering* 43(4): 236-242.

Taylor, C.L., Cluff, L.S. 1977. Fault displacement and ground deformation associated with surface faulting. ASCE special conference, Lifeline Earthquake Engineering, New York, USA: 338-353.

Ulusay, R., Aydan, O., Hamada, M. 2001. The behaviour of structures built on active fault zones: examples from the recent earthquakes of Turkey. *In proceedings,* A Workshop on Seismic Fault-Induced Failures – Possible Remedies for Damage to Urban Facilities, Japan Society for the Promotion of Science, Tokyo, Japan: 1-26.

Van Dissen, R., Heron, D., Becker, J., King, A., Kerr, J. 2006. Mitigating active fault surface rupture hazard in New Zealand: development of national guidelines, and assessment of their implementation. *In proceedings,* 8th U.S. National Conference on Earthquake Engineering, San Francisco, USA: Paper No. 633, 10 p.

Acknowledgments: We would like to thank the landowners for kindly allowing access to their properties during this stressful period. LiDAR images (Figure 2) are courtesy of ECan and NZ Aerial Mapping Limited. We thank Ursula Cochran and Jim Cousins for their critiques that substantially improved this paper.