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The Performance of Structures Subjected to Surface Fault Rupture during the Mw 6.0 South Napa Earthquake, California, USA

J. Cohen-Waeber¹, R. Lanzafame², J. Bray³, N. Sitar⁴

ABSTRACT

The August 24, 2014 M_w 6.0 South Napa Earthquake produced significant surface fault rupture that extended 12-15 km northward from the epicenter, which affected a West Napa residential neighborhood near its northern terminus. The Geotechnical Extreme Events Reconnaissance (GEER) Association deployed teams to investigate the effects of ground failure on infrastructure, including detailed mapping of residential properties damaged by surface fault rupture. Observations of damage and modes of failure of different foundation types show that stiff structures such as reinforced concrete mat foundations, were able to decouple from the underlying ground movements, and performed satisfactorily. Conversely, structures anchored to the ground across the rupture zone, such as with pier and grade beam foundations, did not perform as well.

Introduction

Napa Valley is an agricultural region 60 km north of San Francisco, California, USA, well-known internationally for its viticulture. The City of Napa is its principal municipality, with a population of nearly 80,000, and is located on the Napa River which flows south into the San Francisco Bay. The valley is filled with Holocene and Pleistocene alluvial deposits with thicknesses from 10 m to 160 m, generally consisting of moderately to poorly sorted sand, gravel, silt and clay. Late Tertiary volcanics underlie the sediments and are exposed in outcrops along the hills flanking the valley. The quaternary sediments and older volcanics are underlain by marine sedimentary rock throughout the basin.

Seismic activity in the San Francisco Bay area is associated with the western transform boundary of the North American plate, accommodating approximately 40 mm/yr of dextral shear and generally oriented north-northwest. The West Napa Fault zone is considered to be a minor part of this fault system, located between the larger Hayward-Rogers Creek and Concord-Green Valley fault zones to the West and East, respectively. Most recently, the North end of the West Napa Fault zone produced the M_w 5.0 Yountville-Napa Earthquake of 2000. This event is colloquially referred to as the “chimney-quake” due to predominant structural damage to brick masonry chimneys.

On August 24, 2014 10:20:44 (UTC), a magnitude M_w 6.0 earthquake occurred along the West

¹ PhD Candidate, Civil and Env. Eng., Univ. of California Berkeley, Berkeley, USA, jwaeber@berkeley.edu

² PhD Candidate, Civil and Env. Eng., Univ. of California Berkeley, Berkeley, USA, rlanzafame@berkeley.edu

³ Professor, Civil and Env. Eng., Univ. of California Berkeley, Berkeley, USA, bray@ce.berkeley.edu

⁴ Professor, Civil and Env. Eng., Univ. of California Berkeley, Berkeley, USA, sitar@ce.berkeley.edu

Napa Fault Zone, with an epicenter located approximately 8 km southwest of Napa (N 38.220 W 122.313). The earthquake produced 12-15 km of clear surface fault rupture toward the northwest from the epicenter. This is the first documented case of surface fault rupture in Northern California since the 1906 San Andreas event. As illustrated in Figure 1, two rupture traces were mapped West of Napa, trending North-Northwest, with the main (western) and secondary (eastern) strands exhibiting up to 46 cm and 8 cm of dextral offset, respectively (Hudnut et al. 2014). Seismic damage was significant and four months after the event, state and federal disaster assistance had already exceeded \$30 million (USD); and the total economic damage has been estimated at as much as \$1 billion (USD). Remarkably, damage due to liquefaction or landslide induced ground deformations was relatively insignificant in the entire region.

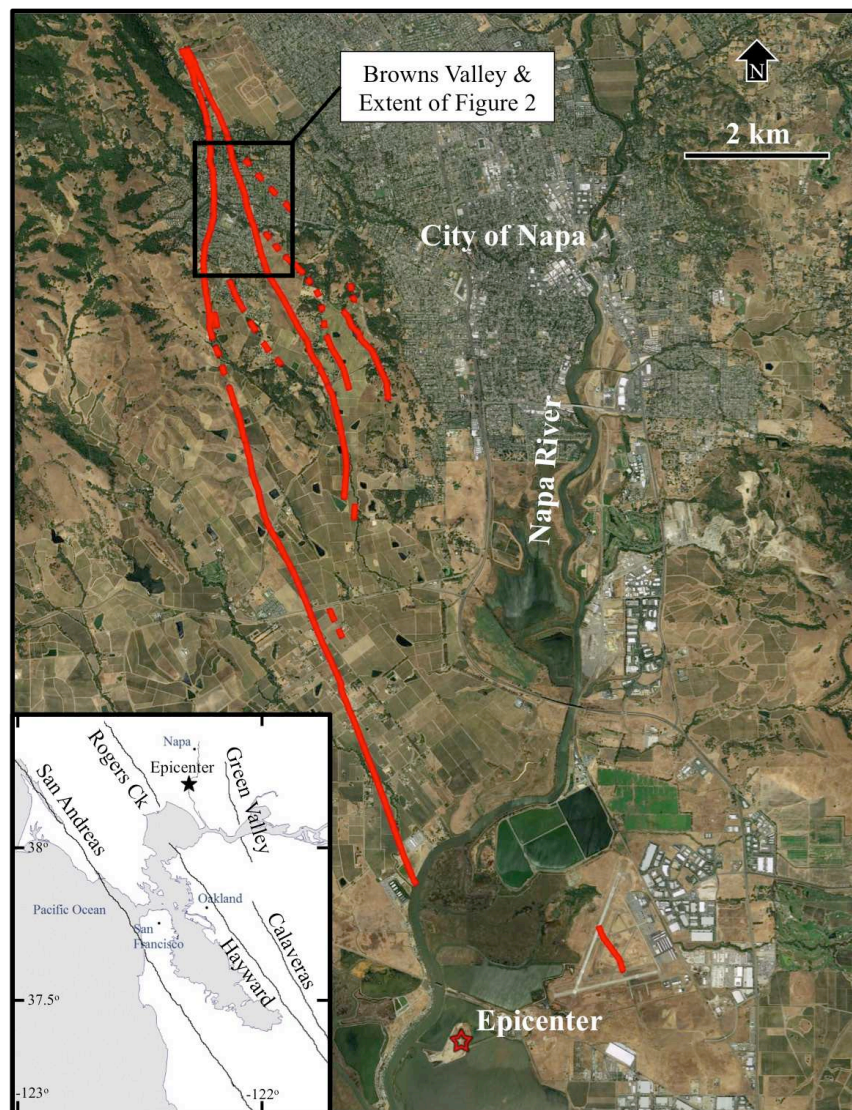


Figure 1. Surface rupture trace of the August 24, 2014 M_w 6 South Napa Earthquake.

In response to the South Napa Earthquake, the National Science Foundation (NSF) funded Geotechnical Extreme Events Reconnaissance (GEER) Association deployed teams throughout

the region to investigate its effects (Bray et al. 2014). A significant part of this effort involved detailed mapping of surface fault rupture related damage to structures in the Browns Valley area. This paper describes the expression of damage and modes of failure for different foundation types and is based on the mapping effort performed during the weeks following the earthquake by Bray et al. (2014).

Browns Valley Area

Structural damage due to shaking during the South Napa Earthquake was prevalent in the historic downtown Napa. However, principal damage to residential structures in the western Napa area of Browns Valley was due to surface fault rupture, along two coherent fault strands (Figure 2). Offset along the main (western) strand within Browns Valley was 10-20 cm (a maximum of 46 cm was measured 1-2 km to the south; Bray et al. 2014), and decreased progressively to the North (Hudnut et al. 2014). Smaller offsets of 2-8 cm were measured along the eastern strand (Hudnut et al. 2014). To ensure safe occupancy, California State regulation requires structures in areas affected by damaging earthquakes to be inspected by trained professionals, soon after the event. Based on the severity of their damage, structures suitable for only brief entry are assigned yellow tags and those not suitable for entry are assigned red tags. In the Browns Valley, most damaged and tagged structures were located on or near surface fault rupture, and red tagged structures were exclusively located along the main strand (Figure 2). The tagging system was used to guide the field mapping effort by the GEER teams.

Structural Performance Mapping

The structural damage associated with surface fault rupture in the Browns Valley area was mapped between August 25 and August 28 and detailed maps of damage to individual structures were produced (Bray et al. 2014). While not all tagged structures were mapped, damage to properties on or adjacent to the primary trace of the fault was mapped with a focus on tagged structures, and to the extent possible given time constraints and subject to property owners' permission. In total, of the approximately 60 residences along the main fault strand alignment within Browns Valley (outlined in Figure 2), exterior damage was mapped at 39 residences and 26 structures were mapped in detail. Though similar damage occurred along the secondary (eastern) strand, only one residence was mapped in detail, also due to time constraints, for a total of 27 structures mapped in detail (Bray et al. 2014). In each case, major damage was documented (including measurements and photographs) and drawn to scale, concentrating on structural damage and ignoring cosmetic damage, as illustrated in Figure 3.

Observations of Structural Damage

Structures in the Browns Valley area are generally one and two-story single family type wood frame buildings, constructed in the 1960's and 1970's. The neighborhood southwest of the intersection between Browns Valley Road and Buhman Avenue is also built on fill placed by the late 1960's. Observed damage to these structures due to surface fault rupture can be subdivided into three general categories:

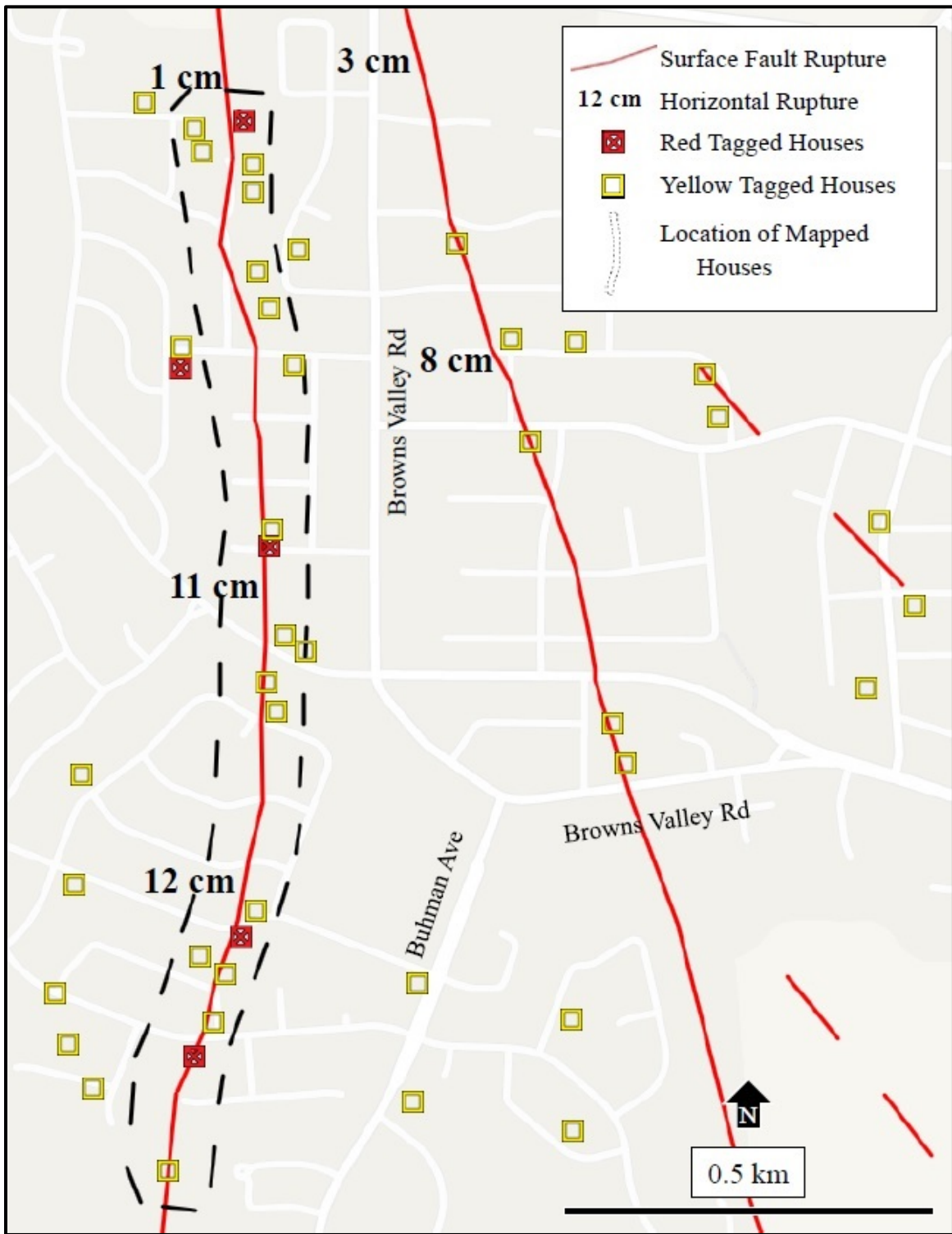


Figure 2. Surface rupture trace of the South Napa Earthquake through Browns Valley, illustrating magnitudes of displacement and approximate damaged property locations. [Note: not all red and yellow tagged structures were visited by the GEER team]

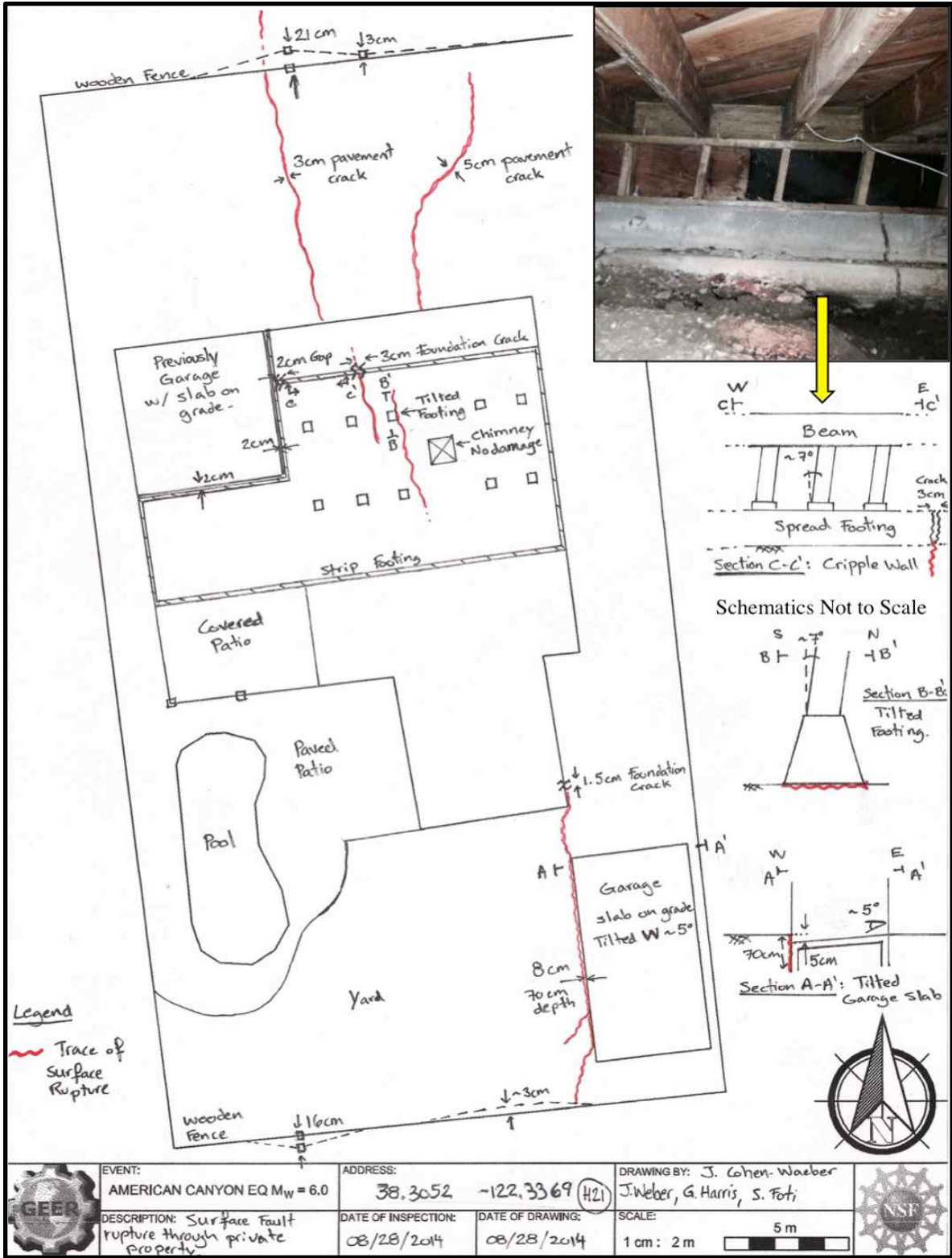


Figure 3. Detailed damage map for a structure on strip footings affected by surface fault rupture in the Browns Valley area. Photo inset shows Type I and II damage.

Type I: Cracking of reinforced concrete and concrete masonry components within structures ranged from cosmetic cracking of swimming pool patios to cracking of structure foundations (Figure 4). Damaged structures included: foundation elements (cracks up to 5 cm wide); non-foundation unreinforced and reinforced concrete slabs (cracks up to 8 cm wide); and curbs and sidewalks (i.e., buckling due to compression).

Type II: Displacement between structures and adjacent ground or structures included: separation between foundation or non-foundation elements and adjacent structures (up to 10 cm) or adjacent ground (up to 14 cm); settlement (up to 8 cm); movement of light structures (up to 27 cm); and displacement along linear features (i.e., retaining walls and fences; up to 3 cm). Horizontal and vertical displacement of structure walls relative to the underlying foundations reached 6 cm and 3 cm, respectively, and generally produced the most significant damage in this category.

Type III: Cracking of paved and unpaved areas at the ground level (Figure 4) included tension and compression features in paved (i.e., asphalt) and unpaved surface, and was a clear indicator of fault trace location (for both main and eastern strands). These features ranged from thin fissures to deep open cracks or buckled asphalt and soil mounds. This damage mode was consistently mapped in a narrow alignment that is very consistent with surface fault rupture as mapped by Hudnut et al. (2014), and this type of damage away from the fault trace is negligible. Asphalt cracking reached depths of 50 cm and horizontal offsets up to 20 cm; buckling reached a maximum height of 24 cm. Rupture of unpaved surfaces reached maximums of 13 cm horizontal offset and 76 cm depth.

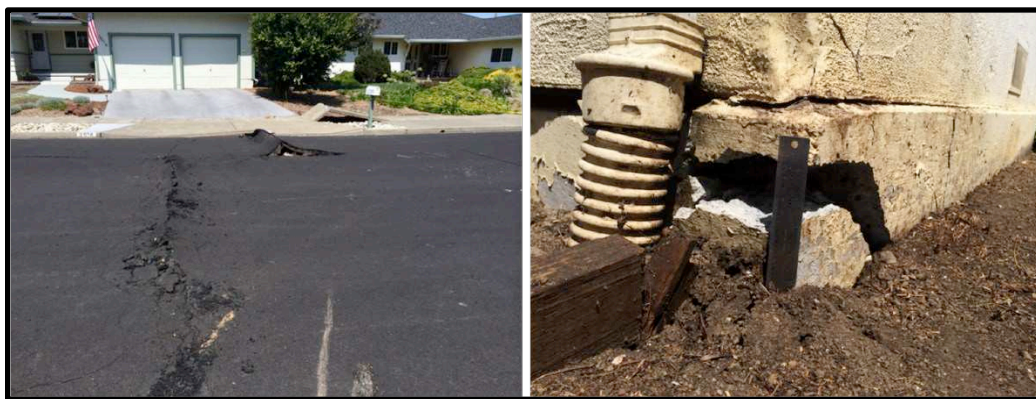


Figure 4. (Left) Type III damage in street; negligible damage to left structure, significant damage to right structure, including (Right) Type I foundation damage.

Observations of Structural Performance

Of the 27 structures for which detailed maps were made, 19 were constructed on strip footing foundations, whereas the other 8 had pier and grade beam foundations. Table 1 summarizes the frequency of damage types associated with each type of foundation. Perhaps the most significant observation related to structural performance mapping is that nearly half of all mapped structures had foundation damage, with 75% of the damage confined to pier foundations.

Strip footing foundations are a common construction practice for these single-family residential

structures in California. They generally consist of a perimeter wall supported by a shallow spread footing, and individual footings supporting wooden floor beams spanning the building footprint. As observed from the displacement of these structures relative to the surrounding ground (damage Type II), the shallow nature of spread footings allowed for a relative decoupling from the ground surface and the structure slid in response to ground deformation. Due to a lack of rigidity, however, structures built on strip footing foundations also experienced damage from angular distortion, expressed as both Type I and Type II damage. As such, these structures experienced significant through-going surface rupture causing visible damage though they generally performed well.

In contrast to strip footings, structures supported on pier and grade beam foundations are anchored to the ground. They consist of a reinforced concrete perimeter wall tied by concrete grade beams and supported over reinforced concrete piers down to variable depths, and are not able to accommodate differential ground deformation. As a result, these structures experienced significant cracking of the reinforced and unreinforced concrete elements as well as shearing and cracking of the building elements (Type I damage).

Finally, two of the observed structures on strip footing foundations had recently been seismically retrofit. Despite their direct alignment with the fault trace, they exhibited a general lack of damage. The addition of thickened and reinforced concrete slabs and structural moment frames allowed the stiffened structures accommodate deformation from the surface rupture because they were essentially decoupled from the ground.

Table 1. Damage summary of residential structures affected by surface fault rupture.

Type*	Description	Strip Footing (19 total; 70%)	Pier/Grade Beam (8 total; 30%)	Overall (27 total)
I. Cracking of concrete or masonry elements	Foundation	6 (32%)	6 (75%)	12 (44%)
	Non-foundation	9 (47%)	4 (50%)	13 (48%)
II. Displacement	Between structure and foundation	4 (21%)	1 (13%)	5 (19%)
	Other	16 (84%)	6 (75%)	22 (81%)

*Type III damage does not relate to foundation type

Conclusion

Few opportunities exist to examine the effects of surface fault rupture on infrastructure in urban environments. This is of particular importance in California where active faulting is expected to produce significant surface rupture through densely developed areas such as along the Hayward fault in the San Francisco Bay Area. Similar setting occurs in other parts of the world such as in Wellington, New Zealand, which sits atop the Wellington fault. Much like in Browns Valley, construction in these areas consists largely of single-family wood frame structures with spread footing, pier and grade beam or mat foundations.

Surface rupture from the South Napa Earthquake clearly shows what modes of failure might be

expected of these types of construction and the benefits of seismic retrofits. While the surface fault rupture hazard cannot be avoided in areas where faulting was not recognized prior to development, the observed performance of robust structures constructed on stiff foundations, such as moment frame buildings constructed on reinforced, thickened mat foundations, shows that they are able to decouple from the underlying ground movements. Conversely, structures that have foundations that are anchored across the fault rupture zone, such as pier and grade beam foundations, do not perform as well since all of the underlying ground distortion is transmitted up to the superstructure.

It is important to acknowledge that these observations do not take full consideration of the multitude of environmental factors associated with surface rupture, such as different fault characteristics, soil properties and thickness, and are applicable primarily to strike slip fault displacement. Further work is required to investigate any correlation with subsurface soil profiles in the Browns Valley area, or with observations from other instances of surface rupture.

Acknowledgments

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