EERI Earthquake Reconnaissance Report:
2019 Ridgecrest Earthquake Sequence

July 2020

A product of the EERI Learning from Earthquakes Program
INTRODUCTION

Contributed by Kate Scharer, Brian Swanson, Tim Dawson, Elizabeth Cochran, and Ben Brooks.

The Ridgecrest Earthquake Sequence began the morning of 4 July 2019 with an M6.4 earthquake at 10:33 a.m., closely following several small foreshocks. The epicenter of this event was roughly 11 miles (18 km) east-northeast of Ridgecrest (Figure 1) within the Naval Air Weapons Station China Lake (NAWS-CL). Seismic and geologic data established that the M6.4 earthquake occurred along a steeply dipping northeast-trending strike-slip fault with left-lateral slip. This earthquake and preliminary reports of damage in Ridgecrest and Trona and associated ground cracking triggered a response by earthquake scientists and engineers throughout the region. A California Earthquake Clearinghouse was established in Ridgecrest to help coordinate the scientific response effort and to share data.

![Figure 1. Epicenters of M6.4 and M7.1 ruptures indicated with focal mechanisms. Rupture mapping highlights northwest-trending M7.1 ruptures and northeast-trending M6.4 rupture (Kendrick et al., 2019).](Image)

Black lines are Quaternary-active (Jennings and Bryant, 2010).²

Following the M6.4 quake, numerous aftershocks occurred in proximity to the northeast-trending fault trace and began migrating along a northwest-trending zone. The largest of these quakes was an M5.4 event that occurred at 4:07 p.m. PDT on July 5 (Figure 2). The M7.1 event occurred at 8:19 p.m. (PDT) and was again centered on the NAWS-CL, about 6 miles northwest of the M6.4 epicenter. The focal mechanism of the M7.1 event and subsequent observations confirmed this earthquake occurred along a steeply dipping, northwest-trending, right-lateral strike-slip fault (Figure 1). Whereas the M6.4 rupture propagated unilaterally to the southwest from the epicenter, the M7.1 rupture propagated bilaterally to the northwest and southeast and crossed the M6.4 trace.
Figure 2. Earthquakes in the month following the Ridgecrest sequence (Image: Morgan Page). The U.S. Geological Survey issued regular aftershock forecasts following these events based on the temporal evolution of the sequence, tuned with regional rate parameters. The information was widely used by NAWS-CL, local emergency response, and the media.

The M6.4 and M7.1 produced strong to violent shaking in the Indian Wells and Searles Valleys, causing the most significant impact to the towns of Ridgecrest and Trona and the NAWS-CL (Figure 3). The M7.1 was felt as light shaking as far away as Las Vegas and Los Angeles, 140 and 125 miles away, respectively. Economic impacts to the region were modest for this magnitude, as most of the building stock is resistant to strong shaking, the population density is fairly low (approximately 35,000 people in the epicentral region), and no surface rupture crossed through population centers. Rather, the epicenters, much of the strongest shaking, and the surface ruptures from both the M6.4 and M7.1 occurred on the NAWS-CL; available estimates to repair and rebuild damaged facilities are $5.2 billion USD (USNI News, 2019).3

Figure 3. ShakeMap intensities for (a) M6.4 and (b) M7.1 ruptures illustrate how shaking extent broadly scales with magnitude.
2 GEOSCIENCES

Contributed by Kate Scharer, Brian Swanson, Tim Dawson, Elizabeth Cochran, and Ben Brooks.

2.1 Tectonic Setting

The Ridgecrest earthquake sequence occurred in a tectonic region located northeast of the southern San Andreas Fault known as the Eastern California Shear Zone (Figure 4). This region of Southern California is characterized by broad, low-elevation valleys and rugged mountain chains with elevations that exceed 5,000 feet (1,500 m). The linear, northwest-oriented valleys contain a network of faults that have produced many of the largest earthquakes in Southern California in the last 30 years, including the 1992 Landers earthquake (M7.3), the 1999 Hector Mine earthquake (M7.1), and now the 2019 Ridgecrest sequence. Each of these earthquakes occurred on strike-slip faults, and the ground on either side of the fault slid horizontally past the other.

Geologists, seismologists, and geodesists moved quickly to observe these events; several teams from academic institutions and state and federal agencies were on the ground the night of July 4, able to make early observations and begin to install instruments to record the earthquakes and ground motions. The following sections summarize that activity.

2.2 Surface Rupture

The earthquake ruptured on a set of discontinuous faults along the eastern side of the Indian Wells Valley, including the Little Lake, Airport Lake Fault Zones, and unnamed fault traces to the southeast (Jennings and Bryant, 2010; Monastero et al., 2002). Some of the rupture occurred on fault traces known to have moved in the last 11,000 years and are thus considered “active” and defined as Alquist-Priolo Earthquake Fault Zones by the California Geologic Survey. Surface
rupture occurred along 11 miles (18 km) of the M6.4 rupture and 31 miles (50 km) of the M7.1 rupture (Figures Figure 1, Figure 5, and Figure 6). Both ruptures are fairly linear, and both terminate at their southern end with a set of subparallel splays. Based on field mapping of offset features, the main shock rupture has a central, 10-km–long plateau of high slip ranging from 3 to 4.5 m that rapidly falls to less than 0.5 m to the northwest and less than 1 m to the southeast, for a total length of 50 km (Kendrick et al., 2019). The M6.4 slip distribution also has a central plateau with approximately 1-m left-lateral offsets over 5 km and <50-cm offsets over the remainder of its 18-km length (Kendrick et al., 2019). These rupture lengths and slip amounts are fairly typical for the respective earthquake magnitudes (e.g., Wells and Coppersmith, 1999).
2.3 Seismology

The 2019 Ridgecrest sequence occurred in a region where several seismic swarms have been identified since the 1980s. These swarms include an energetic sequence in 1995 that began with a Ml 5.4 earthquake and included over 4,500 aftershocks within the first 2 months (Hauksson et al., 1995). The 2019 Ridgecrest M7.1 mainshock rupture is bounded to the north by the Coso Geothermal field, an area of active geothermal production that generates ongoing, low-magnitude seismicity (Feng and Lees, 1998; Schoenball et al., 2016). The southern end of the rupture is bounded by the Garlock Fault, a nearly east-west–striking major transform structure in Southern California (Davis and Burchfiel, 1973). Past seismicity in the area of the Ridgecrest events illuminates a complex set of northwest- and northeast-striking conjugate faults (Hauksson et al., 1995). The 2019 sequence similarly activated conjugate structures, with the M6.4 foreshock occurring on a northeast-striking left-lateral fault and the M7.1 mainshock occurring on a northwest-striking right-lateral fault. The aftershock distribution suggests that multiple subparallel and conjugate fault segments were activated by the sequence.

![Figure 7](image)

(a) Map of seismic and geodetic installations and deployments following Ridgecrest. White symbols include permanent SCSN stations (diamonds), temporary stations [squares, circles, and hexagons by U.S. Geological Survey (USGS) Pasadena, USGS-Albuquerque Seismological Laboratory, and The University of California Riverside (UCR), respectively], and USGS-Southern California Earthquake Center-UU nodal deployment (green circles and lines). Cyan symbols show permanent and campaign GPS stations (triangles, diamonds, and squares by USGS, UCR, and Scripps Institution of Oceanography (SIO), respectively). Red lines are 2019 rupture from Kendrick et al. (2019), and orange lines show Holocene-Latest Pleistocene faults from California Geological Survey (CGS) (Jennings and Bryant, 2010). (b) Map of the National Center for Airborne Laser Mapping lidar collection completed week of 29 July 2019. Blue regions will have the highest resolution (80 pts/m2), and regions in green and yellow will receive moderate (25 pts/m2) coverage. Data will be provided on OpenTopography when processing is complete.

The early portion of the sequence was recorded by permanent Southern California Seismic Network (SCSN) stations (Figure 7). The permanent network provided decent azimuthal coverage of the events, with somewhat higher station densities to the northwest of the sequence. Additional temporary seismic stations were installed within the first few days of the mainshock to increase the number of stations close to the rupture and to improve coverage to the south and east of the sequence (Figure 7). These arrays provide very local measurements of ground motions from moderate aftershocks, including several M5 aftershocks that are useful for calibrating ground motion prediction equations. The data will also aid
in improving the resolution of aftershock depths and determining source properties of the aftershocks. These seismic installations will likely remain in place for a period of 6 to 12 months and were led by researchers from the U.S. Geological Survey and University of California, Riverside. A series of short-term dense deployments of nodal seismometers also occurred within the first few months of the mainshock. These deployments were primarily composed of fault-crossing arrays at several locations along the Ridgecrest surface rupture as well as across a section of the Garlock fault where a swarm of events occurred following the Ridgecrest mainshock. Additionally, a grid of nodes was deployed across a ~40 km by 40 km region centered on the mainshock for using in imaging crustal structure. Nodal deployments were led by the U.S. Geological Survey, Southern California Earthquake Center, and University of Utah (UU). Figure 7 shows the distribution of permanent and temporary stations near to the Ridgecrest ruptures.

2.4 Geodesy

Geodetic deployments by several research teams began immediately following the 4 July 2019 earthquake. The work included reoccupations of existing benchmarks for the purposes of coseismic displacement field determination and establishment of new sites for the purposes of postseismic displacement field determination. Teams from University of California Riverside (UCR) reoccupied a pre-existing network of campaign locations, and the USGS established two Global Navigation Satellite System (GNSS) sites where the surface rupture cut Highway 178 (Figure 7). On July 5, 1 hour after the M7.1 event, the USGS similarly established two GNSS sites across the surface rupture for that event. In the days and weeks following, USGS established nine new sites and reoccupied four existing sites. Many of the continuously operating stations were meant to provide GNSS support for the Airborne LIDAR collection that occurred during the week of July 29 (Figure 7). Off the base, USGS reoccupied existing benchmarks within 60 km of the epicenters of the M6.4 and M7.1 events and has four campaign sites running off base. UCR and Scripps also occupied a total of 13 additional stations, providing excellent coverage to the western and southern portions of the rupture.

2.5 Opportunities to Advance Knowledge

2.5.1 Crustal Behavior and Fault Zone Architecture from Seismicity and Geodesy

This is the first earthquake in Southern California for which a dense and rapid deployment of campaign GPS stations, additional seismic stations, and nodal arrays were completed. Data collection from these instruments is ongoing and will allow scientists to explore the material evolution of the crustal properties surrounding the faults that ruptured and investigate the temporal evolution of seismicity and material properties.

2.5.2 Improve Aftershock Models and Conveyance of that Information

During the Ridgecrest sequence, the USGS provided aftershock models that convey the likelihood of future earthquakes greater than M5, M6, and M7 over daily, weekly, and monthly intervals. The current forecast method uses the temporal pattern of the earthquake sequence and is updated regularly to reflect the evolution of the seismicity. In addition to refining the presentation of the aftershock forecast, future forecasts will likely include information about the location of the aftershocks so that spatial changes in the seismicity patterns are also included (https://www.usgs.gov/natural-hazards/earthquake-hazards/science/could-m71-ridgecrest-ca-earthquake-sequence-trigger-a?qt-science_center_objects=0#qt-science_center_objects).

2.5.3 Characteristics of Surface Displacement and Rupture

A team of over 70 geologists have completed mapping of the surface rupture, measuring the surface displacement across the fault wherever features such as tire tracks, fence lines, and gullies define the offset. Satellite data have collected similar data but typically over a wider aperture; comparisons of these data sets allow us to understand how the localization of slip varies along the rupture. Such data sets are valuable for engineering projects with fault-crossing infrastructure and provide clues into the dynamics of rupture.

2.5.4 Postseismic Transients and Crustal Behavior of the Eastern California Shear Zone

The Eastern California Shear Zone is unique as a region where geodetic estimates of slip rate greatly exceed the geologic rate. In the region of the Ridgecrest sequence, for example, the modeled geodetic rate is ~7 mm/year, while the geologic rate is close to 1 mm/yr (Peltzer et al., 2001; Oskin and Iriondo, 2004; Amos et al., 2013). The difference is thought to result, in part, from postseismic transients related to the Landers earthquake, and it emphasizes the usefulness of geodetic data to understand crustal rheology and potential regions with heightened seismic hazard due to strain transients.
3 GEOTECHNICAL IMPACTS

Contributed by Jonathan Stewart.

The Geotechnical Extreme Event Reconnaissance Association (GEER) partnered with several organizations, including the U.S. Geological Survey, the California Geological Survey, the U.S. Navy, the Southern California Earthquake Center, and local utilities to collect perishable data and document the important impacts of the events.

Critical geotechnical features of this event are extensive left-lateral (M6.4 event) and right-lateral (M7.1 event) surface ruptures over fault segments of variable complexity and width as well as across extensional and compressive step-over zones.

Liquefaction and lateral-spreading features were documented in Trona and Argus, which are located on alluvial and lacustrine units along the margins of Searles Lake. Subsequent work has found substantial liquefaction within Searles Lake, which is largely a dry lakebed. Liquefaction effects on structures were documented in Trona.

Surface fault rupture and liquefaction effects were documented using field (ground) mapping and aerial imagery at various resolutions. The aerial imagery has been interpreted to develop digital elevation models that are posted to DesignSafe, where they are publicly available. More information about GEER data collection methods is described in Chapter 8.

Over 1,200 ground motions were recorded from the foreshock and mainshock alone, with many additional aftershock records. The data demonstrate significant impacts of site response and rupture directivity on ground-motion attributes. The scaling of ground motions with distance from the source is reasonably well captured by Next Generation Attenuation-West2 ground-motion models.

More information about the geotechnical impacts of the Ridgecrest Earthquake Sequence can be found in the GEER report (Stewart, 2019)13.

4 LIFELINES

Contributed by John Eidinger, Jeff Bachhuber, and John Dai.

The Ridgecrest M7.1 main shock earthquake of 5 July 2019 was a strong earthquake with extensive surface fault rupture that affected the communities of Ridgecrest and Trona, California. The main shock was part of a complex sequence of earthquakes and surface faulting, including an M6.4 foreshock with surface fault rupture and many M3 to M5.7 aftershocks.

4.1 Gas System

Pacific Gas and Electric Company operates the natural gas system in this area. The gas system in the area includes several types of infrastructure, including transmission pipelines, distribution mains, service laterals, and meters.

4.1.1 Transmission Pipes

Surface faulting occurred through two gas transmission pipes; one rupture (left lateral slip) was across a 150-mm (6-inch nominal diameter) pipeline related to the July 4, M6.4 foreshock, and the second (right lateral slip) was across a 250-mm (10-inch nominal diameter) pipeline associated with the M7.1 mainshock. The amount of offset at the two pipeline fault-crossing locations ranged between about 30 and 50 cm. Both pipes are heavy-wall welded steel and responded to fault rupture by bending and deforming without leakage. Within a week after the earthquake, both of these buried pipes were uncovered and inspected; no gas leaks were noted. Then, segments of both pipelines were replaced with unstressed new pipe extending about 45 m (150 ft) to either side of the fault crossings.

Surface faulting did not extend through any distribution pipes or service laterals.

4.1.2 Distribution Pipes

About 440 km of distribution pipe were exposed to shaking with peak ground velocities up to 40 cm/s. Gas leak surveys were conducted after the earthquake. Leaks were found along 31 gas distribution mains, mostly 50 to 100 mm (2- to 4-in. nominal diameter). In the Trona area, the bulk of the distribution mains are steel. In the Ridgecrest area, the bulk of the
distribution mains are medium-density polyethylene (plastic). Liquefaction in the South Trona area may explain some of the concentrated damage in that area.

4.1.3 Service Laterals and Meters
A total of 324 leaks on service laterals were found. The majority of these leaks represent the normal number of minor leaks in the distribution system that occur over the course of a year from nonseismic effects (e.g., corrosion). Service laterals were found to have about 10 times the leak rates as compared to distribution mains. About 60% of all leaks were on the risers to aboveground meters.

All leaks located within a few feet of residences (or locations with higher potential for gas accumulation) were repaired within a few days.

4.2 Electric System

Southern California Edison owns and operates the electric system for this area. The electric system in the area includes several types of infrastructure, including aboveground high-voltage (66 kV to 115 kV) transmission lines, high-voltage substations, and low-voltage distribution feeders.

4.2.1 Substations
There are six substations (66 kV to 115 kV) that were exposed to PGA between 0.15g and 0.40g. All substations were designed with some level of seismic detailing, including anchorage of transformers, seismic-designed buildings, and seismic-designed battery racks. There was one broken lightning arrester (needs replacement), but this did not result in an outage. A few disconnect switches were misaligned and needed to be repaired. One transformer tripped, likely because of oil sloshing. Many distribution circuit breakers tripped because of a combination of wire slapping and damage in feeders. An older wooden switch rack was flexible and resulted in deformed supported rigid aluminum bus. A battery charger failed.

4.2.2 High-Voltage Transmission
There are hundreds of 115-kV wood-pole-type transmission structures in the region exposed to PGA > 0.15g, of which more than 30 were exposed to PGA > 0.3g. None of the poles were directly exposed to surface faulting. None of the poles collapsed because of inertial shaking. On one transmission pole, cross arms for a lower level distribution line were damaged. Initial review suggests that this was due to slack-related issues because of differential movements of adjacent poles; these poles were in a liquefaction zone.

4.2.3 Low-Voltage Distribution Feeders
The Ridgecrest and Trona areas use both underground and aboveground distribution feeders. None of these feeders were originally designed with any seismic force considerations. There was a variety of types of damage, including initial swaying of overhead feeders that resulted in automatic opening and closing of circuit breaks at substations (these caused momentary outages), several broken wire situations, several locations where wire slapping was severe enough to trip the circuit break and require a patrol along the feeder to fix damage and then re-energize the feeder (these caused outages with several hour durations), damage to several pole-top transformers (internals and secondaries), several locations of broken cross-arms, and more. Below-ground feeders had a lower repair rate than overhead feeders. No below-ground feeder is known to have undergone PGDs because of fault offset or liquefaction or landslide.

4.2.4 Power Outages
Most of the power outages were related to damage within the distribution system or sloshing of oil in transformers. Nearly all electric service was restored to all customers within 24 hours after each of the large M6.4 foreshocks and the M7.1 main shock.

4.3 Bridges

Contributed by Mark Yashinsky.

There are five small highway bridge structures within 14 miles of the earthquake epicenter. All of these bridges performed well, and there was no sign of structural damage caused by the earthquake.
The Route 178/395 Separation (50 0438) was designed as a two-span cast-in-place (CIP)/prestressed (PS) box girder bridge with span lengths of approximately 108 ft. (but one span was buried under the embankment). The superstructure is supported by reinforced concrete (RC) open-diaphragm abutments that are founded on cast-in-drilled-hole (CIDH) pile footing foundations. An elevation view of the bridge (Figure 8) is shown below.

Figure 8. Elevation view of 178/395 separation (–117.80, 35.65).

This structure, built in 1974, was designed in accordance with American Association of State Highway and Transportation Officials (AASHTO) dated 1969 with Revisions and as supplemented by Bridge Planning and Design Manual. No seismic design information was available. The inspection was conducted by walking on and under the bridge. In this inspection, the bridge deck, abutments, and joints were inspected. The findings are summarized as follows:

1. The transverse cracks found on the westerly approach AC are not related to these earthquakes as indicated in a maintenance inspection report dated 25 August 2017.
2. No damage was identified in this inspection.

The Brown Road UC (50 0340), shown in Figure 9, is a four-span RC box girder bridge that is supported by RC integral two-column bents and open-diaphragm abutments. All foundations are 16”∅ CIDH pile footings. This is a highly skewed bridge with a skew angle of 45°.

Figure 9. Elevation view of Brown Road UC (117.82, 25.67).

This structure, built in 1966, was designed in accordance with AASHTO dated 1964 with Revision and as Supplemented by Bridge Planning and Design Manual. No seismic design information was available. Based on current seismic design standards, the seismic deficiencies are identified and summarized as follows:
1. At Bent 3, the main reinforcements of the columns are connected to the dowels that are precast in the footing (Figure 10). As pointed out by Memo to Designers 20-4, this connection type poses some seismic deficiency. The insufficient lap length and confinement may not be able to maintain the fixity in order to develop the plastic capacity of the columns.

2. At Bents 2 and 4, the shear capacity of the pin key at the bottom of the column may be inadequate to transfer the lateral force to the foundation because no transverse reinforcement exists in the pin key.

3. The joint shear design in the bent cap is inadequate according to Seismic Design Criteria (SDC) 7.4.5.

Figure 10 shows the displacement records from the July 5 event. In a comparison of the displacement time histories at deck level and ground level at Bent 3, the in-phase movement (moving in the same direction) with similar maximum displacement can be identified (transverse direction: Chapter 4 and Chapter 7, longitudinal direction: Chapter 5 and Chapter 8). This in-phase movement implies that the relative displacement between the deck level and ground level is small. This may be part of the reason that no damage was found in the inspection. The maximum displacements are listed in the Table 1.

![Displacement records](image)

**Table 1. Selected instrumentation records**

<table>
<thead>
<tr>
<th>Bent 3</th>
<th>Deck level</th>
<th>South column ground level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acceleration (time)</td>
<td>Displacement (time)</td>
</tr>
<tr>
<td>Transverse</td>
<td>-0.60g (24.6 s)</td>
<td>11.6 cm (29 s)</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>0.33g (24.7 s)</td>
<td>15.2 cm (31.6 s)</td>
</tr>
</tbody>
</table>

1. The displacement at column bottom of Bent 3 did not cause any structure damage.
2. Both abutment slopes are eroded, which is not related to the earthquakes as indicated in maintenance inspection report dated 22 June 2017.
3. No Damage was identified from this inspection.
The N SR 14/S US 395 Separation (50-0479R) is a three-span CIP/PS box girder bridge supported by the single-column bents and seat-type abutments, which are founded on class 70 pile footing foundations. The elevation view of the bridge is shown in Figure 11.

![Elevation view of SR-14-395 separation (~117.87, 35.70).](image)

The structure, constructed in 1993, was designed in accordance with 1983 AASHTO with Interims and Revisions by Caltrans. The peak ground acceleration is 0.6g for seismic design. Based on the current seismic design standards, the seismic deficiencies are identified and summarized as follows:

1. No flare gap is provided at top of the flared column, which will increase the shear demand on column (SDC C7.6.3.1).
2. There was inadequate joint shear design according to 7.4.5 of SDC 2.0.
3. The ratio of the column diameter to structural depth is greater than 1 ($D_c/D_s = 5.5/5 = 1.1$), which may pose difficulty to meet joint shear requirement as pointed out by C7.6.2 of SDC 2.0.

The inspection was conducted by walking on and under the bridge, by which the bridge deck, columns, abutments, and joints were inspected and pictured. This visualized inspection indicates that the bridge components are in good condition, and no damages were identified in this inspection.

It should be noted that although a number of seismic deficiencies are identified by as-built review, no bridge damage was found during the field inspection. Based on the instrumentation records on Brown Road bridge (Br# 50-0340), it is believed that the maximum ground acceleration at the bridge site is smaller than the design value and did not cause any structural damage in the July 4 and July 5 events.

The Aqueduct R178 at PM 87.6, built in 1930 (Figure 12), is a single-span structure. No bridge number or as-built were available for review. The structure type is unknown. Based on the site inspection, it is likely a CIP RC slab superstructure supported by diaphragm-type abutments at both ends of the structure. No damage was identified during this inspection.
The Freeman Gulch Bridge (50 0014) is a two-span steel girder bridge with RC slab supported by RC pier wall and closed-end cantilever seat-type abutments. Figure 13 shows an elevation view of the bridge. The structure, constructed in 1947, was designed in accordance with 1941 AASHTO and Bridge Department Supplement dated 1943. No seismic design information was provided in as-built plans. The structure was retrofitted in 1993, but the seismic design loading cannot be found from as-built plans. In this retrofit project, the new cross frames were added at abutments, and thrust blocks were installed at bent and abutments, respectively. The inspection was conducted by walking on and under the bridge. The bridge deck, columns, abutments, and joints were inspected and pictured. Some cracks were found on the pier wall and deck. As noted in maintenance inspection report dated 5 June 2017, these cracks were not related to the two earthquake events. No earthquake damage was identified during this inspection.
4.4 Ridgecrest Wastewater Treatment Facility

*Contributed by Fred Turner.*

After the M6.4 foreshock, the Ridgecrest Wastewater Treatment Facility observed minimal damage but lost power and relied on emergency power generation. During the M7.1 mainshock, the facility’s clarifiers were damaged, misaligned, and inoperable because of the sloshing of sewage. The facility also experienced breaks in the water lines, and the emergency generator was no longer functioning. The China Lake Naval Air Weapons Station provided military personnel to help restore functions, and, as of mid-September, it was reported to be fully functional.

5 STRUCTURAL IMPACTS

5.1 Overview

*Contributed by Wayne Chang and Ken O'Dell.*

One may be surprised by the apparent limited structural damage observed in the city of Ridgecrest resulting from the 5 July 2019, M7.1 earthquake. Several factors likely contributed to the observed performance and limited damage, including age of the buildings, use of light construction materials, and directionality of the principal ground motion. From available USGS data, it appears the fault rupture was directed toward the Northwest, with much of the ground motion energy concentrated toward the Naval Air Weapons Station, China Lake, sparing the city of Ridgecrest from the highest intensity ground shaking from the M7.1 event. The USGS Shakemap indicates the city of Ridgecrest experienced shaking intensity in the modified Mercalli intensity (MMI) 7.6 range (Station Q0072; Lakeland St., Ridgecrest, CA; PGA 0.332g), while the estimated highest MMI for the M7.1 event was 8.8 (Station CCC; Christmas Canyon China Lake; PGA 0.569g). A specific station record was not documented within the city of Trona; however, Shakemap contours suggest similar intensity was experienced in Trona as that felt in Ridgecrest.

The limited observed structural damage may also be a result of the type of buildings in Ridgecrest. Most buildings in Ridgecrest consist of light wood-frame structures supported directly on concrete stem walls or reinforced concrete masonry “big-box” type warehouse and retail buildings. The light wood-frame structures tend to be less susceptible to the earthquake damage because of the lightweight construction materials and high lateral shear capacity and redundancy from both interior and exterior walls. Similarly, the perimeter reinforced concrete masonry walls of the big-box buildings typically have excessive lateral shear capacity. As result, these buildings are less susceptible to significant damage during earthquakes.

Additionally, most of the buildings in the city of Ridgecrest were constructed in conformance with the requirements of modern structural engineering provisions. With most of the city developed after the 1970s, modern structural detailing would have been incorporated in the building codes to which the structures needed to conform. These buildings are less likely to sustain major damage than those built without these modern structural engineering provisions.

Nevertheless, there was some significant structural damage observed in this earthquake event. The roof collapse at the Ridgecrest Cinema and the damage observed at roof truss connections to concrete masonry pilasters at Our Savior’s Lutheran Church Parish Hall resulted from well-known vulnerabilities of inadequate wall ties between concrete or concrete masonry walls and flexible diaphragms as well as inadequate connections between the roof trusses and concrete or concrete masonry pilasters failing to transmit the out-of-plane wall forces concentrated by the pilaster action. This seismic event highlights the importance to retrofit these known deficiencies to avoid significant structural damages and possible collapse. Provisions for recommended retrofit procedures to mitigate these deficiencies are available in current standards, including the International Existing Building Code.

While the extent of observed damage resulting from the M6.4 and M7.1 events was limited, several lessons can be learned and others reinforced.

Perhaps on top of the list of learned lessons, this event sequence clearly highlights that the Richter Magnitude of an earthquake is not the definitive measure to be used in estimating the probability of damage. Rather, the intensity of ground shaking, within the areas of concern, is a far better gauge of the potential severity of anticipated damage. Although most familiar to the public, the Richter scale can be misleading, as it does not adequately correlate ground shaking,
intensity, and directionality. As evidenced in Ridgecrest and Trona, these parameters provide a better basis for setting initial expectations for anticipated building performance.

Earthquake intensity maps appear to indicate much of the high-intensity shaking was confined to a localized zone outside the city of Ridgecrest and within the boundaries of the Naval Air Weapons Station, China Lake. While preliminary USGS intensity maps indicate a high shaking of IX (modified Mercalli scale), shaking intensity in and around the city of Ridgecrest is estimated to be between MMI VII and VIII. A similarly useful measurement in estimating damage, in lieu of Richter Magnitude, is the estimated peak ground acceleration (PGA). Preliminary data from USGS recording stations indicate a high PGA of 0.569g to the southeast of Ridgecrest, while the PGA recorded within the city limits was only 0.332g. In comparison, the 1994 Northridge Earthquake had an MMI intensity of IX with a PGA recorded as high as 140.2g [Station: OBS_2 x Granada Hills (Kaiser-P)] within the heart of the San Fernando Valley. So, while the Richter Magnitude of the Searles Valley Earthquake was higher than that of the Northridge Earthquake (M7.1 vs. M6.7), the recorded ground accelerations within the built community were much lower in Ridgecrest than those recorded in the San Fernando Valley. In this comparison, the ground acceleration and intensity parameters provide a far better prediction in assessing the level of damage resulting for the Searles Valley versus Northridge events.

The surveyed damage in Ridgecrest also reinforces the lessons learned previously regarding the need for direct load paths to transmit out-of-plane wall forces into and across flexible diaphragm. As exhibited by the failure of the wall anchor at the Ridgecrest Cinema, cross-grain bending of the wood ledger is not a direct load path. Failure of the wall anchorage as it pulled away resulted in collapse of a portion of the cinema roof. Interestingly, the Concrete Masonry Unit wall rebounded to its near plumb condition, and observation of the failure was not possible or discernable from the exterior of the building. This added the lesson, at least for these authors, that, in some cases, an exterior-only rapid assessment may not be adequate to properly identify a vulnerable building after an earthquake.

Another previous lesson confirmed by damage exhibited in the Parish Hall for the Our Savior’s Lutheran Church relates to the concentration of out-of-plan forces at pilasters. The cracking exhibited within and near the integral pilasters clearly defines the need to ensure connection of main roof elements, in this case trusses, to the pilasters that can accommodate not just a uniform wall anchor force but also an increased force level. This higher-than-uniform (per foot of wall tributary to the diaphragm interface) force must recognize that the integral pilaster will collect and concentrate forces from the wall based on a relationship of the wall panel to pilaster stiffness.

While exhibiting minimal exterior damage, the Balsam Street Downtown Building (111 Balsam St, Ridgecrest) highlights the need to address deformation compatibility considerations, especially when completing building additions. The exiting building appears to have been built in at least two phases, with the first likely having been a single-story masonry structure. A second phase of construction appears to have added a second story wing over the adjacent parking lot. In providing open parking bays below this addition, the use of a moment frame or cantilever columns appears to have resulted in a deformation incompatibility between the flexible two-story wing and the adjacent stiff single-story structure. This incompatibility is exhibited at the interface of the stair stringers, which appear to have acted as struts between portions of the building. (See Figure 14)
In contrast to the city of Ridgecrest, the town of Trona, located approximately 20 miles to the northeast of Ridgecrest, appears to have experienced more substantial damage. First developed in the late 1800’s and formally established in 1913, Trona is nearly 50 years older than Ridgecrest, which was incorporated in 1963 following 20 to 30 years as a small support community for the then Naval Ordinance Test facility. Situated on the slight slope of an alluvial fan between the base of the mountains south of Argus Peak, the town’s age and geography provide further lessons.

Trona provides an opportunity to study an older building inventory stock constructed during the early foundations of building codes and other regulations intermixed with newer structures constructed to similar standards as those in Ridgecrest. In Trona and the smaller community of Argus, just to the south, structure damaged related to acceleration of the building is most notable in the older buildings with heavy and informal building materials, such as unreinforced stone masonry and concrete masonry construction. Damage observed in these structures predominantly consisted of in-plane shear failure of the masonry walls and out-of-plane flexural and anchorage failure.

Of significant note, the damage in Trona’s downtown area provides excellent examples of the phenomenon of liquefaction-induced lateral spreading (see Figure 15). Liquefaction has been a design concern for many years; however, the main design focus tends to be liquefaction-induced settlement and the effects of differential settlements across a given building. In Trona, lateral spreading, evidenced by the down-slope spreading of the alluvial fan materials, resulted in a number of buildings having damage that appeared to telegraph up from the foundations rather than moving down because of acceleration of the superstructure. These examples highlight the need to ensure foundation connectivity, similar to diaphragm continuity, across the building.
While not widespread, these examples highlight the lessons learned in Ridgecrest and Trona.

5.2 China Lake Naval Air Weapons Base

Contribute by Fred Turner.

The great majority of damage caused by the earthquakes was to Federal government–owned facilities at the China Lake Naval Air Weapons Station (NAWS) northeast of the City of Ridgecrest. However, because of military security concerns, the NAWS has not disclosed details about the nature of the damage. A total of $200 million was initially awarded to the station on a voice vote of Congress in July. On September 18, $585 million was proposed to be added to the fiscal year 2020 budget as the first tranche of multiyear investments in the replacement of 84 damaged buildings and repair of another 146 buildings. Overall, NAWS losses are projected to be nearly $4 billion, which is more than half of the base’s $5.2 billion replacement cost (Ridgecrest Daily Independent).

5.3 Single Family Homes

Contributed by Wayne Chang, Maria Mohammed, and Andrew Martinez.

Most residential buildings in Ridgecrest appear to be of modern construction, likely built after the 1970s. Single-family homes are typically one- to two-story structures and consist of stucco exterior walls as shear walls with on-grade foundations. Very little damage was observed for such structures in Ridgecrest, mainly because of the age of the homes and the lack of structural irregularities, such as cripple walls, soft stories because of large openings, or falling hazards.
from chimneys. Additionally, increased lateral capacity was also provided through engagement of interior drywall-sheathed partition walls acting as shear walls. The damage observed at some residential buildings was isolated to nonstructural components, such as fence walls, chimneys, and finish veneers. Some masonry fence walls collapsed fully or partially because of lack of proper reinforcing or anchorage to the foundation (see Figure 16).

![Collapsed masonry fence wall.](image1)

More damage was observed in the Cities of Trona and Argus. Most single-family homes in these cities are also single-story structures with stucco exterior walls or lightly reinforced masonry walls as shear walls. The age of construction of these homes appears to be likely in the 1940s and 1950s. Most of the masonry homes had diagonal cracks at the building corners (see Figure 17).

![Diagonal cracks through masonry walls.](image2)
The main structure of the wood-framed homes performed relatively well. Most damage was observed at buildings with structural irregularities or with connections for exterior nonstructural components. At wood-framed homes with raised concrete stem wall foundations, damage was observed along the interface between the wood sill and the concrete stem wall through horizontal cracks in the stucco (see Figure 18).

![Figure 18. Horizontal cracks at sill plate to stem wall interface.](image)

Partially collapsed or fully collapsed chimneys were observed at most homes in the city (see Figures Figure 19 and Figure 20).

![Figure 19. Chimney damages.](image)
Partial collapse of veneer components was also observed at homes with brick veneers (see Figure 21).

A significant number of the homes in Trona and Argus are not well maintained or appear to be abandoned. It is difficult to distinguish whether some of the structural damage observed is due to the earthquake or due to insufficient upkeep.
5.4 Performance of Manufactured Homes

Contributed by Kelly Cobeen.

5.4.1 Introduction

This discussion addresses observations of manufactured homes in the City of Ridgecrest and surrounding areas following the July 2019 Ridgecrest Earthquake Sequence. Out of approximately 13 mobile home parks (MHPs) confirmed to be present in the City of Ridgecrest (Figure 22), nine were surveyed. Also surveyed were three MHPs in communities just outside of Ridgecrest as well as a notable number of manufactured homes located on individual private lots at the north end of Ridgecrest and to the west between Ridgecrest and Inyokern. The noted observations were made on 20 and 21 July 2019 and 8 and 9 August 2019.

![Map of Ridgecrest](https://example.com/map.png)

*Figure 22. Map of Ridgecrest showing the 13 MHPs confirmed to be in Ridgecrest. MHPs with red dots were surveyed; MHPs with black dots were not.*

5.4.2 General Observations

The nine MHPs surveyed within the City of Ridgecrest were the larger and more heavily populated of the total of 13. These range in size from 20 to 110 installed homes, with some additional vacant home sites. Though a number of the MHPs were at or near full capacity, at least three were significantly below capacity, and two were below 50% occupied. A handful of homes appeared to be in the process of being installed at the time of the earthquake. A large number of the MHPs are concentrated at the north end of Ridgecrest, with eight MHPs occurring in a four-block by five-block area bounded by North Downs Street to the west, West Inyokern Road (State Route 178) to the North, North China Lake Boulevard (State Route 178/395) to the east, and West Ward Street to the south (Figure 23). The MHPs in this group tended to be situated on sites with little or no park improvements or shared facilities. Other MHPs, distributed through the city, generally had paved loads, curb and gutter improvements, and shared park facilities.
Two MHPs to the west of the City of Ridgecrest were surveyed, one on the outskirts of Inyokern and the other on State Route 178 between Ridgecrest and Inyokern. The Inyokern MHP only had a handful of manufactured homes, all installed on unimproved lots, and these had no obvious indication of significant damage. The State Route 178 MHP had approximately 70 homes on improved lots in what appeared to be a long-standing housing community; there was no apparent sign of damage to these homes.

The Town of Trona and the Trona MHP are located about 20 miles east and north of the City of Ridgecrest. The population in this area is understood to have dropped significantly over a number of years because of changing operations at the nearby Searles Valley Minerals Company. The park was observed to have a total of approximately 110 home sites but only six installed homes. Observed from a distance, there was no apparent sign of significant damage to these homes. This MHP is identified to be located in San Bernardino County, whereas the other MHPs fall in Kern County.

At the north end of Ridgecrest and extending to the west toward Inyokern, a substantial number of manufactured homes were observed to be installed on individual privately owned lots. These ranged from improved lots within the city proper to lots beyond the city (believed to be under the jurisdiction of Kern County) on minimally improved lots. These homes were generally without readily observed damage, although a small handful were seen to have shifted on or fallen off their supports.

### 5.4.3 Observed Home Support Systems

The majority of damage to manufactured homes in past earthquakes has been to the site-installed support systems between the factory-manufactured home and the ground. These support systems have been observed to be highly vulnerable to earthquake damage. Significant damage to carports, decks, and other site-installed structures attached to homes has also been observed. To date, only minimal earthquake damage to the factory-manufactured home units has been observed, except in the case of fire, in which total loss of the home often results.

Damage to the support system typically involves the home falling completely off the supports, falling partially off the supports, or shifting on the supports; the amount of shifting can range from small to significant. When surveying the MHPs, it is often possible to identify homes that have fallen off of their supports (Figure 24) or have shifted significantly (Figure 25) because the aluminum or wood panel skirts surrounding the support system are disrupted or opened in order to make repairs. Where the skirting has been opened, the support system can be observed. Each home will have a system to support gravity loads (gravity system). Homes may or may not have additional systems designed to resist lateral wind and earthquake loading.
The great majority of the homes were observed to have steel gravity piers (Figure 26). The piers were most often supported on preservative-treated wood boards, which are identified as foundations for purposes of manufactured home installation. These gravity piers were sometimes fastened to the wood foundation or to the chassis beam that they are supporting (Figure 24), but many were found to not have any attachment (Figure 27). Not having any attachment makes the pier particularly vulnerable to rolling over when the home shifts because of earthquake loading. In general, fastening of the steel piers is seen in more recent home installations (approximately 1990s or more recent) but is unusual in older home installations. Gravity pier types have been found to vary regionally in California and other western states. A limited number of Ridgecrest homes were observed to be supported on precast concrete gravity piers instead of steel gravity piers. None of the homes were observed to be supported on dry-stacked concrete masonry blocks, another commonly seen support system. A limited number of homes were observed to have the gravity piers (whether steel or concrete) sitting directly on the ground instead of on a wood foundation.
Since September 1994, the California Code of Regulations, Title 25, Division I, Chapter 2 (State of California, 2013)\textsuperscript{15}, has required that a wind tiedown system be installed on newly installed or relocated manufactured homes in the state of California. This requirement comes from SB 750, passed in July 1994, in response to devastating damage to manufactured housing in the 1994 Northridge Earthquake. These California requirements are noted, however, to fall below the minimum federal standards set by the Manufactured Home Construction and Safety Standards (Office of the Federal Register, 2019)\textsuperscript{16}. Further discussion of applicable regulations can be found in FEMA P-1024 (Federal Emergency Management Agency, 2015)\textsuperscript{17}. Very few manufactured homes in Ridgecrest were observed to have any type of wind or earthquake bracing system. This is considerably different from observations following the 2014 South Napa Earthquake, where a small but noticeable number of homes had wind and earthquake bracing systems installed.

For Ridgecrest manufactured homes, there are three notable items to report regarding support systems:

1. Five homes were observed to have proprietary wind and earthquake bracing systems installed (Figure 28). Of these, four homes appeared to be just completing installation, and it is assumed that the systems were in place at the time of the earthquakes. The fifth home is believed to have had the system installed for a longer period of time. The bracing system appears to be of the type identified by the California Department of Housing and Community Development to be an Engineered Tie-Down System, as required by the State of California for new home installations and homes moved to new lots. There was no observed falling or shifting of the support system in these five homes.
2. One home was observed to have a recently installed wind bracing system (Figure 29). This system uses steel straps and helical ground anchors and is commonly used in areas of high wind. Though the system is permitted by both California law and minimum federal standards for both wind and earthquake bracing, there is little information on earthquake performance of this type of system. Based on discussions with neighbors, the system was installed several months before the earthquake. Although there was evidence of some shifting of the stabilizer plates, the system appeared to have resisted the earthquake loading without observable damage.

3. In a number of instances, hardware from steel strap tie-down devices was observed to be partially installed or abandoned under existing homes (Figure 30). It appeared that homes previously installed on these sites had been secured with wind bracing systems, but use of the systems had not continued as new homes were brought in. At a number of the home sites in the Trona MHP, abandoned ground anchorage devices could be observed. This suggests that anchorage for high wind was common in these locations at some time in the past.
5.4.4 Observed Performance

Among the MHPs, performance was observed to be widely varying. Of the approximately 600 homes included in the nine surveyed MHPs in the City of Ridgecrest, approximately 30, or 5%, fell off of their supports. The number with shifting significant enough to trigger reinstallation is roughly estimated to be up to two-times this number. Although 5% is a small number overall, there were three parks with no fallen homes, two parks with one to two fallen homes, and one park in which approximately 25% of the homes had fallen or shifted significantly. For this one park, more than half of the units received an Unsafe to Occupy placard (or “red tagged”), keeping the units from being reoccupied until reinstallation could occur. This performance can be compared with site-built homes, for which no significant damage was reported to have occurred.

Observed damage was much more significant at the MHPs at the north end of town (previously discussed). These homes were closer to the epicenter and would have experienced somewhat higher ground shaking, were generally installed on unimproved lots, and were generally older, smaller homes with aluminum siding and skirting. Examples of damaged homes can be seen in Figures Figure 31, Figure 32, and Figure 33. The rest of the surveyed homes were located in the southern part of Ridgecrest, were generally installed in communities with site improvements, and were often, but not always, newer (Figures Figure 34 and Figure 35). Though significant damage was less prevalent in these parks, it did occur, as seen in Figures Figure 36 and Figure 37.
Figure 32. Home in MHP at the north end of Ridgecrest.

Figure 33. Homes in MHPs at the north end of Ridgecrest.

Figure 34. Homes in MHP at the south end of Ridgecrest.
Figure 35.  Home in MHP at the south end of Ridgecrest.

Figure 36.  Damaged home in MHP at the south end of Ridgecrest.

Figure 37.  Damaged home in MHP at the south end of Ridgecrest.
The homes that were observed to have fallen off or significantly shifted on their supports had gravity support systems only and did not have wind or earthquake bracing systems. The majority were older homes with older support systems, lacking fastening to the chassis beam and foundations. In past earthquakes, the damage to homes that had fallen off of their supports did not generally extend up into the occupied home. For several fallen homes in Ridgecrest, however, very significant damage was seen to move up into to the occupied home (Figure 38). As in past earthquakes, falling or significant shifting of homes often causes significant damage to attached structures. This can include site-built add-ons to the occupied home (Figure 39) and the various decks, stairs, ramps, and carports that are commonly added (Figures Figure 40 and Figure 41). Damage to decks, stairs, and ramps can make it difficult for residents to exit these homes following an earthquake.

![Figure 38. Damage to the occupied home wall caused by home falling off its supports.](image)

![Figure 39. Damage to sight-built addition to a home.](image)
Three homes are understood to have been destroyed by fire. In past earthquakes, fires have often started when homes fall over on to their utility hookups. In this case, at least one of the burned homes was observed to not have fallen.

5.4.5 Other Observations

Several other observations made during MHP surveys are potentially of interest:

1. In a number of MHPs, the gas meters and hookups for gas service were located less than 1 ft. away from the side of the home (Figure 42). In some parks, the electrical hookups were located equally close. In these parks, the homes that fell off their supports did not fall toward the utility hookups, but this appears to be by chance. This is significant because if the homes had fallen toward the hookups, there could have easily been significantly more fire damage. Installing homes further away from the utility hookups would appear to be an easy way to make these homes safer in future earthquakes.
2. A number of homes in various MHPs and private lots were installed on what could potentially be permanent foundations (Figure 43), with foundations, foundation walls, and anchorage similar to site-built homes. None of these homes were observed closely enough to verify that they met the construction requirements for a permanent foundation. The number of possible permanent foundations is notably higher than observed in other regions following past earthquakes. This is of significance because installation of permanent foundations should improve the performance of manufactured homes to be similar to site-built homes. Where qualifying permanent foundations are installed, increased options are often available for home financing, which may be helping to drive what appears to be a change in installation practice.

3. In addition to many manufactured homes being located on privately owned lots, several of the MHPs appeared to have homeowners associations, suggesting that the lots and improvements are owned by the residents. These parks had a higher portion of the homes installed on what appeared to be permanent foundations. This is of significance because an increased portion of manufactured homes supported on permanent foundations should lead to better performance of manufactured homes as a group.
4. Though observations in past earthquakes identified relocation of manufactured homes between lots or parks to be rare, there was evidence in Ridgecrest of more frequent relocation of homes. This included one home that was in the process of being moved during observations and other homes believed to have been installed not long before the earthquake.

5.4.6 Conclusions
With there being only limited occurrences of damage to structures overall in the City of Ridgecrest in the Ridgecrest Earthquake Sequence, the extent of damage to manufactured homes makes them stand out as particularly vulnerable. This is consistent with observations following other recent earthquakes (Earthquake Engineering Research Institute, 1996, 2005; Federal Emergency Management Agency, 2015).18,19 The more significant damage appears to have concentrated in older homes with older support systems. Unless changes are made to make the existing manufactured housing stock less vulnerable, it should be anticipated that similar levels of damage will occur in future moderate to major earthquakes.

5.5 Reinforced Masonry Buildings

Fred Turner

Some buildings in the damaged region experienced wall-to-roof connection damage that was not visible from exterior observations alone. One example was the Our Savior’s Lutheran Church Parish Hall, a concrete masonry unit building constructed in 1950. The tops of its wall pilasters were spalled, compromising girder bearings and rendering the building unsafe (Figures 44 and 45). This building remained unoccupied as of mid-September.

Figure 44. Spalled pilaster at girder bearing location.
5.5.1 Roof Collapse
The Ridgecrest Cinemas has eight nested theaters composed of perimeter concrete masonry unit walls with open-web joists with wood chords and plywood roofs. The oldest theater was reportedly built in the 1980s, and additional theaters were added in later years. Because of damage in the M6.4 earthquake on July 4, the theater was closed and unoccupied on July 5. The roof of the oldest theater collapsed in the M7.1 earthquake because of tension perpendicular to wood grain that split wood sills where the roof trusses connected to walls. However, the perimeter walls showed little or no signs of distress (Figures 46 and 47).
Six of the eight cinemas were reopened in late July once the walls around the collapsed roof were braced with raker shores (Figure 48).

Figure 47. Collapsed roof framing inside Ridgecrest Cinemas.

Figure 48. Diagonal raker shores attached to concrete masonry unit wall and new foundations to brace the wall that was no longer braced by a roof that had collapsed inside the Ridgecrest Cinemas. Cargo units intended to limit the public’s exposure to falling hazards.
5.6 Ridgecrest Regional Hospital

Contributed by Marshall Lew.

5.6.1 Hospital Building Safety Board

There are nine buildings that constitute the Ridgecrest Regional Hospital (RRH) (see Figure 49). Three buildings (Main Core, B Wing, and C Wing) have precast/tilt-up concrete walls and are one story in height; these buildings were designed in accordance with the 1964 Uniform Building Code (Main Core and B Wing) and the 1967 Uniform Building Code (C Wing). The Intensive Care Unit Addition is also one story and is of steel braced frame construction designed under the 1973 Uniform Building Code. The D and E Wings are one story and of reinforced masonry construction with wood/metal deck diaphragms; these buildings were designed under the 1985 California Building Code. The Hospital Addition is two stories with a mechanical penthouse and has reduced beam section welded steel moment frames; it was designed under the 2001 California Building Code. There is also a separate central plant of masonry construction, which was recently completed and presumably designed under a more recent edition of the California Building Code.

After the 4 July 2019 Mw 6.4 earthquake, the hospital voluntarily transferred its inpatients to other facilities but kept the Emergency Department in operation. The Office of Statewide Health Planning and Development (OSHPD) inspected the hospital and issued green tags for all the buildings; green tags indicate that there were no restrictions on use or occupancy. Inspection of the facility by the hospital’s structural engineer indicated that there was no structural damage to the facility. Nonstructural dry wall damage was observed mostly on the first floor of the newer Hospital Addition; this was possibly attributed to the taller first floor and movement of the moment frame of the building. Water leaks in the mechanical penthouse of the Hospital Addition caused flooding of the penthouse and leaked into the Operating Rooms and the building’s elevators. The leaks were caused by breakage of the relatively rigid copper water pipes connected to the water pumps supported on isolators; this occurred on three of the four water pumps in the penthouse (see Figure 50).

Figure 49. Ridgecrest Regional Hospital facility map.
As a result of the 5 July 2019 Mw 7.1 earthquake, the hospital lost power because of a failure of a transformer near the hospital; however, the emergency generators performed as expected. There were only six patients in the Emergency Department and no inpatients, as they were previously transferred to other facilities. Inspection of the hospital after the second earthquake by the hospital’s structural engineer still indicated no structural damage, but additional nonstructural damage to the dry walls of the Hospital Addition was observed. Additional water leaks were experienced on the second floor Intensive Care Unit of the Hospital Addition in small water pipes that were part of the constant air volume heating, ventilation, and air conditioning system in the ceiling. OSHPD’s observations of the facility noted that there were no failures or distress of the suspended ceilings and lighting fixtures because of ground shaking.

There was no strong motion instrumentation installed at the RRH facilities. Ground motions were recorded at Station NSMP 5419 located at China Lake Naval Weapons Center, less than 1 mile from RRH. The maximum horizontal ground motions at RRH has been estimated to be about 0.2g and 0.3g for the July 4 and July 5 earthquake events, respectively. Assuming that the ground motions at China Lake and RRH were similar, a comparison of the China Lake ground motion response spectra for the July 5 earthquake was made with the design spectrum for RRH as shown in Figure 51 as RRH is a little further than the China Lake site, the ground motions were likely lower. The comparison of the spectra indicates that there was sufficient structural capacity relative to the seismic demands of Mw 7.1 event, thus reinforcing the observations that there was no structural damage.
The nonstructural damage observed at RRH in the form of dry wall distress was not unexpected. The good performance of the suspended ceiling and lighting fixtures is affirmation that more attention to the design and detailing of nonstructural elements in more recent building codes has been successful in preventing potential losses and injury. The nonstructural damage was limited in the respect that bracing and support prevented loss of ceiling and lighting support and pipes were braced. However, the lack of proper detailing of the water pipe connections led to the pipe breakages, which could have been avoided if flexible connections were provided.

5.7 Industrial Facilities

*Contributed by Fred Turner.*

5.7.1 Searles Valley Minerals, Inc. Industrial Plant

Searles Valley Minerals (SVM) is a relatively large facility composed of three production plants in Trona, Argus, and Westend and a large mineral reserve on Searles Lake. The areal extent of the reserve is almost 35,000 acres of both private and Bureau of Land Management land (Anderson, C. (2019, November 5). Email). The SVM plant is owned by Nirma, a company based in India. It extracts and steam processes 1.75 million tons of soda ash chemicals annually from the dry Searles Lakebed (Searles Valley Minerals Wiki). Prior corporations owned the plant and maintained the nearby company town of Trona for its employees, currently numbering 700. At its peak, Trona had a population of 6,000 in the 1980s, but its current population is below 2,000 (Trona Wiki).

The two earthquakes on July 4 and 5 caused extensive damage to SVM facilities, including those on Searles Lake. SVM had no injuries associated with these earthquakes. When the initial large earthquake hit on July 4, production ceased. The following 7.1 earthquake on July 5 occurred while the production facilities were offline. Company personnel initially inspected all facility buildings and prohibited entry into many as a precautionary measure until a professional structural assessment could be made.
In the first days after the earthquake, the main focus of the company was repair of the potable water lines to the community of Trona while ongoing assessment of facility equipment was being performed (Figure 52). The County of San Bernardino Fire Department initially red-tagged five SVM-owned buildings in the community. Three of those are located at 13223 Main St., 13217 Main St., and 13211 Main St. The two others are two parts of the same building and are located at 82824 Trona Rd.

![Crew repairing damages potable water line to Searles Valley Minerals. Lines were damaged in many areas and had to be repaired or replaced.](image)

Structural engineers from two outside engineering firms began assessing the SVM facility buildings for structural damage. Of the buildings initially red-tagged by the county, the structural engineers inspected and reassessed the buildings at 13217 and 13211 Main St. and 82824 Trona Rd. as yellow-tagged. Repairs were made to one half of the building at 82824 Trona Rd., and it has been cleared of any tag. The other half of the building remains yellow-tagged. Only the building at 13223 Main St. is red-tagged because of structural damage.

Of the many SVM facility buildings in both Trona and Westend, although there was observable damage, only one building was yellow-tagged because of structural damage. Other buildings had restricted access as a precautionary measure because of damage to nearby equipment that could be a safety hazard to personnel. As the equipment has been repaired and/or replaced, access to these buildings has been restored. After 2 months of repairs, SVM returned to full production (Anderson, C. (2019, November 5). Email).

Damage is reportedly in the millions, but no employees were laid off at the plants (Barnwall, 2019). Other damage documented by SVM includes damage to steel and concrete walkways and supports (Figures Figure 53–Figure 55) and railroad lines (Figure 56: Anderson, 2019).
Figure 53. Many supports for piping and other structures moved or failed.

Figure 54. Weld failures occurred in many walkway and support structures.
Figure 55. Damage to concrete stairs and wall.

Figure 56. Deformed railroad lines at SVM.

The industrial plant did not allow access to Clearinghouse participants to observe damage inside the facility, but views from outside of the plant showed evidence of severe damage to chimneys (Figures Figure 57 and Figure 58) and hollow clay tile walls that were demolished (Figures Figure 59 and Figure 60) (Searles Valley Minerals Wiki).
Figure 57. SVM industrial plant damaged chimneys.

Figure 58. SVM industrial plant repaired chimneys.
Figure 59. SVM industrial plant damaged nonductile concrete building with lower level of hollow clay tile walls removed. Collapsed unreinforced masonry yard wall in the foreground.

Figure 60. SVM industrial plant demolished hollow clay tile walls.
5.7.2 Acknowledgements

Information and images courtesy of Camille Anderson, Searles Valley Minerals.

5.8 Safety Assessment Tagging of Buildings

Contribute by Fred Turner.

The City of Ridgecrest contracts with Kern County for building code enforcement services. At the time of the earthquakes, the City did not have personnel trained and certified as Safety Assessment Program Assessors or Coordinators on site. This contributed to delays in assessing the safety of a proposed emergency shelter, requesting mutual aid to assist staff in conducting assessments, and conducting the assessments. City staff issued a request to Civil Engineers living in Ridgecrest to volunteer to help conduct assessments. After several days of delay, the City asked Kern County’s Emergency Operations Center (EOC) for mutual aid to supplement available resources to conduct safety assessments. The EOC responded with 20 inspectors from Kern County, Bakersfield, Shafter, Lancaster, Palmdale, California City, Stockton, Santa Clarita, and Paramount City as well as three volunteers from the American Council of Engineering Companies and one volunteer from the University of Colorado.

Damage assessments were conducted in Ridgecrest and some buildings in neighboring unincorporated areas, mainly upon request by owners. Systematic assessments of entire neighborhoods were generally not thought to be warranted and thus were not attempted. Some building owners were not available or opted not to contact the Building Department despite experiencing severe damage and in some cases collapses or near collapses. Some occupants and other members of the public were exposed to unsafe building conditions because of actions or inactions by owners and regulators. Several damaged buildings were observed by Clearinghouse participants to have damage that warranted tagging, but the buildings were not tagged.

By comparison, systematic safety assessments of the entire town of Trona and unincorporated parts of San Bernardino County were conducted by county employees.

Overall, as of early August, approximately less than 5% of the building stock in Trona and Ridgecrest were assessed (Figure 61).

![Map showing the distribution of red- and yellow-tagged buildings in Ridgecrest and Trona.](image_url)
In parallel, three state agencies deployed personnel to the region to conduct safety assessments of state-regulated facilities. The Office of Statewide Health Planning and Development deployed personnel at the Ridgecrest Regional Hospital shortly after the M6.4 earthquake and returned after the M7.1 earthquake. The Division of the State Architect for public school assessments and the Housing and Community Development Department for state-regulated mobile home assessments experienced delays in obtaining mission tasking prior to deploying. The Cerro Coso Community College chose to not comply with occupancy restrictions for one of its yellow-tagged buildings (Figure 62).

![Restricted Use Placard](image)

**Figure 62.** Community College buildings remained in use despite a Restricted Use placard that allowed only brief entry to access contents. Damage was later found to include significant structural damage, but the safety assessment was not revised (F. Turner).

### 5.9 Schools

Contributed by Fred Turner.

The Cerro Coso Community College suffered significant structural damage. The Kern County Fire Department estimates losses of almost $2.4 million. Many buildings on campus were yellow-tagged by the Division of the State Architect on Friday, July 12 (Figures Figure 63–Figure 66).
Figure 63. A chevron brace in this community college experienced lateral torsional buckling of its brace-beam above the ceiling (F. Turner).

Figure 64. Diagonal braces buckled out of their plane and damaged gypsum board ceilings in a community college (F. Turner).
Figure 65. This sprinkler head bent when it interacted with the lay-in ceiling (F. Turner).

Figure 66. Buckled light gage steel diagonal brace where it was coped at its stud connection (F. Turner).
6.1 California Governor’s Office of Emergency Services

Contributed by Kevin Miller.

6.1.1 Initial State Operations Center Response

On 4 July 2019, the California Governor’s Office of Emergency Services (Cal OES) responded to the M6.4 earthquake by activating the State Operations Center (SOC). Initial priorities of the Cal OES Seismic Hazards Branch included provision of preliminary scientific and engineering information to the SOC to support state-level operational response decisions. The Seismic Hazards Branch coordinated directly with the State Geologist (California Geological Survey) and others in the scientific community for advice and expertise in understanding what had happened, including historical context and geologic scope/setting, as well as to begin to get an idea of potential scope and impacts to communities and people in the affected area.

On 5 July 2019, an M7.1 earthquake occurred about an hour after the State Operations Center had deactivated from three 12-hour shifts (day, night, day) addressing the impacts of the M6.4 event. At this point, the Governor himself activated the SOC, and both the outgoing and a new incoming shift team reported to the Rancho Cordova facility to brief one another and move forward with the overnight shift. Priorities from the outset included reassessing new damage, injuries, and needs from communities in the affected area and immediate provision of regional response and recovery support. The California Earthquake Prediction Evaluation Council convened on Saturday, July 6, at the request of Cal OES to provide technical expertise and advise the Governor regarding the earthquake event.

6.1.2 Use of Hazus

The Cal OES Seismic Hazards Branch, operating in the SOC, provided scientific information to Management and the Planning and Intelligence Section, Situation Status Unit, to inform overall decisions as well as operations, logistics, and other aspects of the State Operations level response. The Seismic Hazards Branch coordinated with the Federal Emergency Management Agency to secure Hazus Earthquake Loss Estimation modeling to inform requests for federal, state, and local assistance. This modeling also informed an initial request for a Presidential Disaster Declaration of $100 million for public assistance. Three Hazus scenarios were requested as events unfolded: the Ridgecrest M6.4 foreshock, the Ridgecrest M7.1 mainshock, and an M7.5 on the Garlock Fault. The first two scenarios were to estimate community and regional impacts from the two earthquakes that occurred 1 day apart. The Garlock scenario was requested to assess potential impacts should another triggered earthquake happen on an extremely dangerous nearby fault and provide for related contingency planning.

HAZUS analysis based on modeling of the Ridgecrest M6.4 foreshock was as follows:

- $56.2M in total economic losses with the majority ($51.4M) in Kern County
- 2,670 damaged structures
  - 2,340 Affected
  - 330 Minor

HAZUS analysis based on modeling of the Ridgecrest M7.1 mainshock was as follows:

- $100.4 million in total economic losses, with the majority ($99.2 million) in Kern County
- 5,050 damaged structures
  - 4,040 affected
  - 930 minor
  - 80 major
  - <10 destroyed

HAZUS analysis based on modeling of a simulated M7.5 on the Garlock Fault was as follows:

- $1.4 billion in total economic losses, including $575 million in Kern County and $590 million in Los Angeles County
- 62,660 damaged structures
• 50,000 affected
• 10,340 minor
• 1,940 major
• 380 destroyed

6.1.3 Key Elements of Information Provided
The Cal OES Seismic Hazards Branch coordinated with experts from the scientific community to provide regular updates of Aftershock Counts and Aftershock Probabilities. In the nearly 2 weeks the SOC was activated, over 16,000 aftershocks associated with this earthquake event were reported, with many of them greater than M2.5. Aftershocks continued to decline over time (see Figure 67). Tracking aftershocks and probabilities helped advise staffing needs and public safety considerations. Information was provided via constant direct contact with United States Geological Survey (USGS) seismologists as well as published aftershock forecasts located on the USGS earthquake event summary website. Of particular interest for reporting and decision-making were monitoring areas adjacent to the fault rupture from the M7.1 to the north, the Coso Volcanic Field, and to the south, the Garlock Fault.

The Cal OES is a founding management member of the California Earthquake Clearinghouse, and they assisted early on with securing a space in the City of Ridgecrest for the Earthquake Clearinghouse to convene. The Cal OES Seismic Hazards Branch served as a conduit to receive and relay information to and from the Clearinghouse and the SOC. The California Geological Survey opened the Earthquake Clearinghouse in Ridgecrest on 6 July 2019 and conducted daily briefings at 1900 hours.

Aftershocks (14451)

M 0+ earthquakes within 70 km of the mainshock's epicenter. The duration of the aftershock sequence is 11.1 days.

6.1.4 Overall State Response (SOC and Field)
As the event progressed, priorities and objectives coordinated from the SOC evolved on a daily and nightly basis based on operational needs, requests, and issues. The summary of these is as follows:

Priorities:

- Sustain humanitarian assistance efforts
- Protect lives, property, and the environment
- Support shelter operations and any special needs populations
Transition to recovery
Perform damage assessments
Provide recovery programs to impacted populations
Ensure accurate and timely public information

Objectives:

- Maintain the safety of responders and the protection of life and property in the impacted areas
- Support mass care and shelter operations, including resource deployment and staging
- Monitor and support ongoing health and medical needs for the impacted area
- Identify and address access and functional needs integration, including accessible transportation, and other unmet needs
- Assess critical infrastructure and support restoration
- Support community outreach and service programs, including Seamless Summer Meal Program
- Support Local Assistance Center in Trona
- Support Local Assistance Center in Ridgecrest
- Complete joint Public Assistance Preliminary Damage Assessments
- Complete joint Individual Assistance Preliminary Damage Assessments
- Analyze potential impacts and ensure coordinated, timely, accessible, and accurate information to all stakeholders, responding agencies, and state and federal partners
- Recovery Task Force established to assess jurisdiction’s capacity and capability for recovery

6.2 FEMA Response

Contributed by Anne Rosinski.

On 4 July 2019, the Federal Emergency Management Agency (FEMA) stood up a Liaison Officer (LNO) at the California Governor’s Office of Emergency Services (Cal OES) Emergency Operations Center in Sacramento in response to an M6.4 earthquake near Ridgecrest, California. The FEMA LNO subsequently stood down in the evening of July 4 after the M6.4 resulted in minimal damage. FEMA stood up an LNO again on the evening of July 5 after an M7.1 earthquake.

On 8 July 2019, in response to the ongoing Ridgecrest earthquakes, the President signed an Emergency Declaration for the State of California, covering Kern and San Bernardino Counties. The declaration number is FEMA-3415-EM. This declaration authorized the Department of Homeland Security, FEMA, to provide appropriate assistance for required emergency measures, authorized under Title V of the Stafford Act, to save lives and to protect property and public health and safety or to lessen or avert the threat of a catastrophe in the designated areas. Specifically, it authorized FEMA to provide emergency protective measures (Category B), limited to direct federal assistance, under the Public Assistance program at 75% federal funding.

In addition, on 6 August 2019, California Governor Newsom requested that the U.S. Small Business Administration (SBA) declare a disaster for the damage caused by the Ridgecrest earthquakes. On 7 August 2019, the SBA approved California Declaration numbers 16074 and 16075 (Peterson, 2019) for earthquakes occurring 4 July 2019 through 12 July 2019 in the California counties of Kern and San Bernardino; the contiguous California counties of Inyo, Kings, Los Angeles, Orange, Riverside, San Luis Obispo, Santa Barbara, Tulare, and Ventura; the contiguous Arizona counties of La Paz and Mohave; and the contiguous Nevada county of Clark. The application filing deadline was 7 October 2019 for physical damage and is 7 May 2020 for economic injury (Peterson, 2019).

Starting on Tuesday, 9 July 2019, at the request of Cal OES, FEMA conducted Preliminary Damage Assessments (PDA) for Kern and San Bernardino Counties. The counties were not prepared to conduct PDAs, as on that date (4 days after the M7.1), the counties themselves did not know the extent of the earthquake-induced damage. The uncertainty regarding location and extent of damage resulted in delays completing the PDA process. Approximately a dozen residents from Kern and San Bernardino counties in California and one resident of Nevada reached out directly to FEMA R IX Earthquake Program inquiring about availability of disaster-support resources. All inquiries were connected to appropriate state and county resources and contacts.
FEMA participated in Earthquake Clearinghouse nightly briefing calls convened by the State of California. Furthermore, on Tuesday, July 9, FEMA participated on the National Earthquake Hazards Reduction Program (NEHRP) multi-agency coordination call in accordance with The Plan to Coordinate NEHRP Post-Earthquake Investigations (U.S. Geological Survey, 2003)\textsuperscript{25}.

6.3 Hazus Analysis

\textit{Contributed by Jordan Burns.}

Initial U.S. Geological Survey (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER)-based loss estimates for the M7.1 Ridgecrest event, released after manual review 55 min after the event origin time, indicated an \textit{Orange} alert for economic losses (median losses between $100 million and $1 billion) and a very low likelihood of fatalities. Such significant initial PAGER financial loss estimates warranted more detailed loss assessments. Current USGS/FEMA protocol for significant domestic earthquakes entails a coordinated interagency impact modeling process, whereby USGS provides ShakeMap shaking layers to FEMA, who uses those shaking layers to compute Hazus losses over the ensuing hour. USGS then combines PAGER and FEMA losses into a 2PAGER product that summarizes enhanced loss estimates aggregated at the county level and provides spatial details not afforded by PAGER’s global loss model alone (Wald et al., 2019)\textsuperscript{26}. Manual Hazus model runs and collaborative review by FEMA and USGS teams imposes a 2- to 4-hour lag between the release of initial PAGER loss estimates and the release of the more detailed Hazus impact summary.

Following the Ridgecrest event, 2PAGER results were distributed by both agencies to the emergency management community after about 90 min from the origin time (See Table 2); in the future, they will also be provided publicly online as this product matures. In fact, the Ridgecrest Earthquake Sequence afforded an additional opportunity to further evaluate and refine the interagency loss-modeling protocol, which began development in 2017. Losses estimated for Ridgecrest by PAGER and Hazus concurred, both having estimated impacts in the $100 millions.

\textit{Table 2. 2PAGER loss estimates for Ridgecrest M7.1, ShakeMap Version 2 (1 hr, 30 min after origin time)}

\begin{itemize}
  \item $203$ million in total economic losses, including $192$ million in Kern County
  \item 7,204 damaged structures
    \begin{itemize}
      \item 5,471 affected
      \item 1,366 minor
      \item 339 major
      \item 28 destroyed (25 are manufactured housing)
    \end{itemize}
  \item 1,143 households without power
  \item 42 displaced households
  \item 34 nonfatal injuries
\end{itemize}

Hazus model results were refined in tandem with updated USGS ShakeMap data to produce subsequent versions of the 2PAGER product in the days and weeks following the earthquake (Error! Reference source not found.). During these updates, impact estimates increased as a result of ShakeMap refinements—primarily increases in shaking in the epicentral region as a result of additional ground motion and macroseismic observations—and have continued to compare well with observed damage data. We note, however, that the exposed (including many classified) assets and losses at the China Lake Naval facility were not specifically considered in the PAGER or Hazus models, though those impacts were the most extensive.

\textit{Table 3. 2PAGER loss estimates for Ridgecrest M7.1, ShakeMap Version 7 (5 weeks, 5 days after origin time)}

\begin{itemize}
  \item $203$ million in total economic losses, including $192$ million in Kern County
  \item 7,204 damaged structures
    \begin{itemize}
      \item 5,471 affected
    \end{itemize}
  \item 1,143 households without power
  \item 42 displaced households
  \item 34 nonfatal injuries
\end{itemize}
• 1,366 minor
• 339 major
• 28 destroyed (25 are manufactured housing)
  ▪ 1,143 households without power
  ▪ 42 displaced households
  ▪ 34 nonfatal injuries

Direct comparisons between modeled losses and observed data are frequently limited because damage data collected after a major earthquake are generally incomplete and are not analogous with damages modeled in Hazus. However, we translate Hazus-modeled building damage estimates into potential tagging assignments for 2PAGER purposes, which should enable users to understand potential post-earthquake tagging needs. In the weeks following the earthquake, the Hazus team continued coordination with the USGS ShakeMap team to update modeled losses and review significant changes in impact estimates. Based on the current version 7, losses increase somewhat because of higher ground motions in the epicentral area. Detailed Hazus results are summarized below and available online (https://disasters.geoplatform.gov/publicdata/NationalDisasters/2019/RidgecrestCalifornia_Earthquake_July2019/Data/Hazus/).

In addition, given the possibility for increased seismicity along the Garlock Fault system following the Ridgecrest earthquake, the Hazus team worked with the USGS and the Pacific Disaster Center to develop an updated Garlock scenario for FEMA Incident Management Assistance Team and Cal OES response planners, including a similar summary of Hazus results and 2PAGER product using an existing USGS ShakeMap scenario. These results helped support emergency management risk planning (https://earthquake.usgs.gov/scenarios/eventpage/bssc2014garlockgcgeshaw09mod_m7p5_se/executive).

Whereas much more detailed loss information is available in Hazus comprehensive model results, this brief summary and the 2PAGER report that accompanies it has been successfully tested during the response phase of other recent events, such as the 4 May 2018, M6.9 Big Island earthquake and the 30 November 2018 Anchorage earthquake. The abbreviated style of Hazus data delivery builds on the successful USGS PAGER alert protocol to provide decision makers with actionable information during the initial phase of response. 2PAGER reports and data can be applied directly toward the Preliminary Damage Assessment performed jointly by FEMA and the State to support potential Presidential Disaster Declarations, as was the case in the Anchorage earthquake (e.g., Thompson et al., 2020)27.

7 CLEARINGHOUSE OPERATIONS


7.1 Physical Location and Virtual Clearinghouse Website

After a major and/or damaging earthquake in California, the California Geological Survey (CGS) is mandated to establish a clearinghouse along with its managing partners, the Earthquake Engineering Research Institute (EERI), the U.S. Geological Survey (USGS), the California Office of Emergency Services (Cal OES), and the California Seismic Safety Commission (CSSC).

Within the first few hours after the July 4 M6.4 Ridgecrest earthquake, consideration to activate the California Earthquake Clearinghouse was strongly influenced by the magnitude of the earthquake and incoming reports of fault rupture, fires, and damage. By 5:00 pm, announcements went out that the Clearinghouse would activate, and representatives from CGS, USGS, and Cal OES at the State Operations Center were working with state-level partners to establish a physical location in Ridgecrest. On the morning of July 5, the Kerr McGee Center, 100 West California Avenue, Ridgecrest, California, was identified as available. The first evening briefing was scheduled for 8:00 pm that evening. It was during that briefing that the M7.1 earthquake occurred, leading to a temporary evacuation of the clearinghouse location. The physical Clearinghouse was operational from Friday afternoon on July 5 until Friday morning on July 12. There was a total of nine evening briefings; six were held in Ridgecrest from July 5 to July 11, and after the Clearinghouse location closed, three more virtual Clearinghouse briefings were conducted on July 15, July 22, and August 12.
The purpose of the California Earthquake Clearinghouse is twofold: (1) it provides the opportunity for all agencies in the field to coordinate reconnaissance efforts, manage access to restricted areas, share findings, and make plans for teams in the field each day; and (2) it links the scientific and engineering communities with agencies and organizations responsible for emergency response and recovery so that their findings can inform the response and recovery efforts.

During its 7 days of operation, over 50 experts visited the Clearinghouse location and participated in reconnaissance activities. Their expertise spanned many disciplines, including geosciences, geotechnical engineering, structural engineering, nonstructural components, insurance, lifelines, transportation, government, risk analysis, and business continuity. They represented over 20 organizations.

This was the first California earthquake with a magnitude and damage sufficient to trigger the establishment of a Clearinghouse since the 2014 Napa earthquake. Like the Napa earthquake, data were collected and displayed in near-real time through the Clearinghouse, and many layers of data, collected by different individuals and organizations, were posted and accessible online.

Lessons learned from the Napa earthquake led a team of CGS geologists and Geographic Information Services (GIS) staff to develop a digital filed data collection system for fault rupture, landslides, and liquefaction. This system, based on Collector for ArcGIS (Esri, Redlands, CA), was utilized by CGS and USGS geologists and either uploaded to a CGSA server in real time or synchronized with the server at the end of the field day. These data were converted to KMZs and GeoJSONS, with daily updates posted to the Clearinghouse website.

As with the Napa earthquake, the virtual Clearinghouse website (http://learningfromearthquakes.org/2019-07-04-searles-valley/) was available to post scientific and engineering observations, photos, and data from the earthquake. This website hosted notifications about reconnaissance efforts, instructions and links to data collection and visualization tools, links to media reports, and preliminary reports by scientific and engineering experts as they became available.

EERI members, geologists, and other earthquake risk reduction professionals contributed to reconnaissance efforts in the following ways:

1. Use of the Fulcrum application to collect and share reconnaissance data. EERI members conducting reconnaissance were encouraged to collect data using the EERI reconnaissance data collection form in the Fulcrum application.
2. Use of the ArcCollector application to collect and share geologic field mapping data
3. Use of EERI Batch Upload Tool to upload photos
4. Communicated reconnaissance plans, providing the opportunity to link with others in the field and share photos or observations
5. Volunteered with the Virtual Earthquake Reconnaissance team by researching specific topics to gain an understanding of the extent of damage in the region
6. Submitted KMZ or keyhole markup language data layers that were uploaded to the visualization map by EERI staff

The backend database that hosts these data, along with the visualization map and virtual Clearinghouse website, will serve as an ongoing and long-term repository and archive for scientific and engineering observations and reports from the earthquake.

The California Earthquake Clearinghouse for the Ridgecrest Earthquake Series had several important accomplishments:

- Field team coordination was supported by EERI, CGS, USGS, and CSSC staff, who operated from the Clearinghouse location to link volunteers and experts conducting reconnaissance in the field.
- Nightly briefings were held at the clearinghouse location and webcast so that reconnaissance teams and volunteers could share daily findings with the research community, the State Emergency Operations Center, the Regional Emergency Operations Center, and FEMA Region 9.
- The Clearinghouse helped the earthquake community make notable progress toward coordinated data archiving of earthquake damage observations by encouraging data sharing and collaboration among the scientific and engineering communities and providing the data collection and visualization tools that facilitate sharing.
Many lessons from this California Earthquake Clearinghouse activation will influence and enhance the response to future earthquakes. Notably, improved communications, training, and advanced coordination are needed to encourage additional organizations and experts to participate more fully in reconnaissance activities. Further improvements are needed in the robustness of the data-collection tools and the functionality of visualization tools. The California Earthquake Clearinghouse managing partners are preparing an After-Action Report that will more completely outline lessons and recommendations for future activations.

7.2 Virtual Earthquake Reconnaissance

_Contributed by Erica Fischer, Manny Hakhamaneshi, Maggie Ortiz-Millan._

The EERI Virtual Earthquake Reconnaissance Team (VERT) is a subcommittee of the Learning from Earthquakes program that was established in 2017 and is composed of over 150 volunteer members. VERT regularly conducts virtual reconnaissance for major earthquakes around the world by reviewing credible online news sources and verified social media accounts to rapidly compile a summary of earthquake impacts.

VERT activated its members on 4 July 2019 following the M6.4 earthquake. VERT volunteers were asked to investigate a variety of topics using credible online resources to develop a rapid summary of earthquake impacts. Over the course of a 4-day activation for the Ridgecrest Earthquake Sequence, the 22 VERT volunteers compiled a summary report covering a wide range of topics, including seismology, hospitals, impacts to buildings, geotechnical impacts, lifelines, transportation, business impacts, emergency response, and fire following the earthquake. The VERT report, “Virtual Earthquake Reconnaissance Team (VERT): Phase 1 Response to M6.4 & M7.1 Searles Valley Earthquakes 07/04 & 7/05/2019,” is published on the Ridgecrest Earthquake Sequence Virtual Clearinghouse website.

7.3 Acknowledgements

City of Ridgecrest for allowing the Clearinghouse to operate out of the Kerr McGee Community Center. EERI’s coordinating role as part of the California Earthquake Clearinghouse was made possible by funding from FEMA.

8 DATA COLLECTION, COORDINATION, AND PRODUCTS

8.1 CGS and USGS Data Collection

_Contributed by Kate Thomas._

The California Geological Survey (CGS) and United States Geological Survey (USGS) used a variety of tools to map geologic effects such as surface rupture related to the Ridgecrest Earthquake Sequence. Although some geologists used traditional analog data collection methods (paper and pencils), most data acquired were digital and allowed for real-time and near–real-time sharing of data among CGS, USGS, and other responding organizations.

Data collection tools used by CGS and USGS field crews consisted of Avenza Maps, handheld Global Positioning System (GPS) receivers, and Collector for ArcGIS (ArcCollector). Avenza Maps is a mobile collection device that can be used on iOS or Android operation systems and allows the user to plot locations and photographs on a basemap. Those data can be exported as a KMZ and text file to be shared with collaborators. ArcCollector is a mobile data collection application created by Environmental Systems Research Institute (ESRI), which interfaces with ArcGIS Online (AGOL) and integrates with all other ESRI products, such as ArcMap and ArcGIS Pro. The ArcCollector application can be installed on any mobile device using an iOS, Android, or Windows operating system. ArcCollector maps can be used “live” through a wireless data connection (cellular or Wi-Fi) or cached to the device if network access is limited or not available. If the map is being used live, data is instantaneously synced to AGOL and to other devices. If the maps are cached, the data needs to be synced manually. When syncing data to AGOL, data collected by others will also be synced down to the device. This allows others in the field to see data their collaborators are collecting in the field as close to real time as possible.

A team of CGS geologists and Geographic Information Systems (GIS) staff first created the Post-Earthquake Reconnaissance Collector application in early 2017 by working together to build a schema that would be useful not only for collection of scientific data on surface rupture, landslide, and liquefaction but also to assist first responders and engineers with information about the severity of building and utility damage. The schema for surface rupture, however,
was adapted during Ridgecrest field reconnaissance to better interface with the database being compiled by USGS and to allow for a more streamlined data collection for field crews. CGS’s intention was to share these data as KMZs, GeoJSON files, and an ESRI geodatabase with responding partners as close to real time as possible. However, because of security issues at Naval Air Weapons Station China Lake (NAWSCL), data and imagery collected on base required review prior to public release. In place of releasing the raw data and photographs in real time as envisioned, the USGS/CGS data compilation team created a stripped-down KMZ for dissemination consisting of observation location and institution that collected the point (see Field Data Compilation section). This KMZ was made available on the Earthquake Engineering Research Institute (EERI)’s Learning from Earthquakes resource page.

Remote sensing data was also acquired and proved invaluable in planning field surveys as well as studying the fault rupture. Ken Hudnut (USGS) acquired helicopter-based, high-resolution aerial imagery using a GPS-enabled Nikon D800 DSLR. These images are being processed using structure-from-motion software to create digital elevation models (DEMs), digital surface models, and orthomosaic images of the surface rupture. These derivative products will be used as base images to produce detailed maps of surface rupture patterns as well as help quantify surface displacements along the fault.

Unmanned Aerial Vehicles, or drones, were flown by many different organizations, such as NASA Jet Propulsion Laboratory, University of Nevada, Reno, Arizona State University, the National Science Foundation funded Geotechnical Extreme Events Reconnaissance Team, and CGS. Drones were used for rapid acquisition of high-resolution digital products for studying and mapping surface rupture, geological features, and other earthquake effects. These data were processed and disseminated rapidly and used to help determine field survey site locations.

Light Detection and Ranging (lidar) uses light emitted from a laser to map structures on the ground. A typical lidar system contains a laser, GPS, and an inertial measurement unit that is used as a mobile system on aircraft and vehicles. The different parts of the lidar system work together to measure the time it takes for a pulse to travel to the ground and reflect back to the sensor, corrects for motion of the vehicle collecting the data, and provides a latitude and longitude for each point or pulse of light emitted. The raw point cloud of each detected reflection can be processed to remove unwanted objects such as vegetation and structures to produce a high-resolution DEM (Figure 68) of the Earth’s surface. Terrestrial-based lidar was collected by Ben Brooks and Todd Ericksen from USGS (Figure 69), using a lidar system mounted to a truck. Brooks and Eriksen collected lidar along portions of the M6.4 rupture on July 5 and were granted access to NAWSCL to survey areas of the high slip along the M7.1 rupture. The National Center for Airborne Laser Mapping (NCALM) was funded by USGS and National Science Foundation to acquire high-resolution aerial lidar for the whole of the surface rupture at 25 points per square meter (ppsm) and at 80 ppsm for areas directly over the fault rupture (Figure 70; Hudnut et al., 2019a; and Hudnut et al., 2019b)28,29. These data are currently being processed and will be released through OpenTopography (https://opentopography.org/) when completed.
Figure 68. Example of a DEM produced from high-resolution truck-mounted LiDAR scan. Resolution is ~2.5 cm. Image: Stewart (2019) Preliminary Report on Engineering and Geological Effects of the July 2019 Ridgecrest Earthquake Sequence GEER-064

Figure 69. USGS Earthquake Science Center Mobile Laser Scanning truck operated by Ben Brooks and Todd Ericksen, scanning the surface rupture near the zone of maximum surface displacement of the M7.1 Searles Valley earthquake. Photographer: Ben Brooks, USGS.
CGS and USGS also made use of satellite-based synthetic aperture radar (InSAR) data, particularly InSAR derivative products such as phase gradient imagery (Xu et al., 2019), to help identify lineaments that could be field checked for surface rupture. These high-resolution data, processed by Xu et al. (2019), allowed field teams to see fractures off the main rupture that might have gone unnoticed otherwise (Figure 71).
8.2 CGS and USGS Data Compilation


This section outlines the key components of compiling data collected by reconnaissance teams following both 2019 Ridgecrest earthquake events. Methods for data compilation and archiving developed during the Mw 6.0 South Napa earthquake of 24 August 2014 (Ponti et al., 2019a) form the basis for the Ridgecrest data compilation, with modifications made to accommodate both the scale and the unique character of fault rupture and ground deformation in the Ridgecrest event. The South Napa earthquake response was one of the first earthquake-effects data collection efforts in which reconnaissance data was mainly collected and disseminated electronically. Compared with the South Napa response, Ridgecrest saw an advance in mobile data collection usage and techniques, which aided in the rapid dissemination of ground deformation information despite the much larger volume of data collected.

Field data collected to document surface faulting and ground deformation features produced by the Ridgecrest Earthquake Sequence consists of the following two primary data sets: (1) field observations at sites that document the character, sense, and amount of ground deformation (e.g., fault slip, dilation) and (2) maps consisting of linework that document the distribution and extent of linear deformation features (e.g., surface fault traces and lateral spreads) or areas of ground failure (e.g., broad scale faulting, areas of slope failure, or liquefaction features such as sand boils). Below, we describe how these types of data were handled for the Ridgecrest earthquake sequence.

8.2.1 Field Observations

The principal challenge for data collection was in extracting, parsing, and translating observations from multiple sources and applications into a standard data schema. The compilation database used for this standardization, modified from that used for compilation of field observations following the M6.0 South Napa earthquake (Ponti et al., 2019a), is a PostgreSQL/PostGIS spatial database consisting of two primary tables: (1) an observations table in which each record contains descriptive information and deformation measurements obtained by a set of observers at a specific site and date/time (represented by point geometry) and (2) a related photographs table that stores photograph metadata, including camera location and view direction, and links to the photograph files that are associated with the observation sites, where applicable.

Shortly following the initial Ridgecrest events, avenues of data sharing were quickly established between USGS, CGS, university researchers, and private entities with USGS taking the lead for comprehensive data compilation. Field researchers provided USGS compilers data in various formats through email, file transfer protocol, and science blogs hosted by the Southern California Earthquake Center, EERI, and USGS. For work at NAWSC, USGS geologists joined CGS teams in the field and began using CGS’s customization of ESRI ArcCollector, which simplified data compilation. Most observations, however, were obtained using non-Collector applications of various types and were transmitted in multiple formats, including spreadsheet tables, GPS tracklogs, reports in portable document format, photographs or scanned drawings, text documents (email, text, or word-processing files), shapefiles, and KML or KMZ Google Earth files.

8.2.2 Non-Collector Observations

Most of the reported non-ArcCollector data consisted of notes, measurements, and photographs documenting the existence and character of ground deformation at a specific locality or site. Over 4,900 field observations were submitted from 19 different entities in the 50 days after the initial shock. These data were manually converted to tabular form, parsed, and transferred into a standardized series of spreadsheets as an interim step to populate the compilation database. Similarly, photographic metadata needed to be extracted from the photograph files, and the photographs were screened for relevance and to meet NAWSC operational security requirements; then, they were organized into directories for archival purposes and dissemination via a USGS ScienceBase data release (Ponti et al., in press).

8.2.3 ArcCollector Observations

Compiling of observations collected using the ESRI ArcCollector simplified the compilation process, as the ArcCollector data schema was designed to closely mimic the compilation. ArcCollector allows for a consistent and disciplined approach to logging ground deformation data. Observations and associated photographs are uploaded to AGOL in real time or near real time depending on internet availability, eliminating the need for interim data transfers. The ArcCollector database schema for surface faulting was still in the development phase when the Ridgecrest earthquakes occurred and was adapted twice from its original design to better mimic the compilation database schema and to simplify data entry. Although this level of uniformity aided data compilation, it did not eliminate the need for compilers to review and
parse data entries. Like non-ArcCollector observations, photographs needed to be extracted from the ArcCollector database, the metadata needed to be extracted, and the extracted photographs still required screening and organizing into directories for archival and dissemination purposes. Combined, over 1,750 observations and over 2,000 photographs were recorded using the three ArcCollector schemas used in the 50 days following the initial shock.

8.2.4 Fault Rupture and Deformation Mapping
Critical to the field effort was the compilation of observations and field mapping to produce provisional rupture maps for situational awareness, field work planning, and dissemination to the public, with a final map of fault rupture and other linear deformation features anticipated for release sometime in 2020 (Ponti et al., in press), in formats similar to what was produced for the South Napa earthquake (Ponti et al., 2019b). Linework contributing to the various versions of the provisional rupture maps released during the response phase were derived from (1) field mapping, (2) tracing of fault rupture from post-earthquake optical imagery, and (3) use of deformation models, i.e., pre- and post-earthquake optical and synthetic aperture radar (SAR) images to produce interferograms and correlation images that highlighted areas of apparent surface dislocations.

8.2.5 Field Mapping
In addition to site observations and slip measurements, many teams also mapped segments of the rupture in the field. Rupture linework was generated in several ways: (1) mapping directly in ArcCollector by either walking out ruptures on foot to characterize the location and extent of visible surface deformation or drawing linework on the mobile device while observing the rupture in the field, (2) recording GPS tracks while walking out the ruptures on foot by using either handheld or survey-grade GPS receivers, and (3) making observations and collecting GPS waypoints along segments of the fault rupture and then subsequently connecting the waypoints and observations to produce a representation of the extent and orientation of fault rupture. Though the field mapping typically produced detailed representations of surface deformation, only a limited portion of the fault zones were directly mapped in the field.

8.2.6 Imagery
Compilers and several field team geologists had access to commercial post-earthquake satellite orthoimage tiles (i.e., from Worldview-2 and Worldview-3, Planet constellation, and Pleiades-1 constellation satellites), from which rupture in high-slip areas (generally > 0.5 m or more of horizontal slip) was visible over certain portions of the rupture area. Several researchers and compilers worked independently to produce representative maps of surface rupture from these various images, which were taken between 5 July 2019 and 14 July 2019. In addition to post-earthquake satellite imagery, several researchers acquired and produced high-resolution orthoimagery and digital surface models by using overlapping ground photographs and aerial imagery obtained during helicopter reconnaissance and from unmanned aerial systems. As with field mapping, linework generated from these high-resolution images are generally highly detailed but are very limited in the extent of rupture mapped.

8.2.7 Deformation Models
Fault rupture maps were also derived from pre- and post-earthquake SAR image products and satellite optical imagery, using radar interferometry and optical image correlation methodologies to identify regions of apparent surface and near-surface deformation over the entire epicentral region. The advantages of these products are their large coverage areas and sensitivity to relatively small amounts of deformation. However, fine-scale rupture detail is not evident in these products, and artifacts may be present, which can lead to potential overinterpretation of the results. In some cases, deformation indicated in these products did not result in visible ground deformation or did not appear to be of tectonic origin. Nonetheless, these products, coupled with verification from ground observations, proved very useful in capturing the overall extent of faulting from the event and for helping to focus field efforts in verifying secondary ruptures.

During the response phase of the Ridgecrest Earthquake Sequence, provisional rupture maps were produced on a regular basis. Compilers at USGS compiled all available rupture linework as above, combined with their own interpretations from post-earthquake satellite images and deformation models, along with point observations of surface deformation to produce provisional maps of the comprehensive rupture.

To preserve as much original detail as possible, each line segment was attributed with information about the origin and provider of the linework as well as a verification attribute containing a qualitative evaluation of how well the line segment represents the extent and character of the fault rupture or deformation feature in the field. Line segments were considered to be verified if they were clearly visible in post-earthquake optical imagery or if multiple observations of fault rupture or deformation occurred along the trend of a feature, such that its continuity and extent as mapped were well-constrained.
Not fully verified segments are those for which there may be one or a few ground observations on the trend of the feature, but for which there is low confidence as to the overall extent and continuity of the rupture segment or, based on observations, the fault rupture occurs over broad areas such that the provisional map representation may not fully represent the character of the rupture. Unverified line segments are derived from imagery or derivative remote sensing products that have not been field checked.

These provisional maps are mashups of the best available information on the fault rupture at the time of their construction and will be continually refined until all field work is completed and image products have been released and processed. Originally provided linework and interpretations are preserved as submitted in the provisional maps with, in the opinion of the compilers, the best representation of fault rupture displayed when multiple linework has been submitted for the same areas. Line segments in the provisional maps are not registered to a single base map, nor are they consistently reconciled against observation site locations. The final rupture map to be released will register the rupture mapping to the NCALM airborne lidar and electro-optical imagery product (Hudnut et al., 2019a), with fault observations also registered to the same base imagery.

### 8.2.8 Dissemination

During the response phase, non-ArcCollector observations and current rupture mapping were shared with CGS and USGS field reconnaissance teams through ArcGIS online map services, which were then provided for download into the ArcCollector application. Field teams could then use these data as a common operating picture as well as to consider where gaps in observations exist and where ruptures classified as “not field verified” prompted site visits. On a periodic basis, all observations and current rupture mapping were released for public consumption in the form of static map graphics and KML files. Map graphics were provided with generalized interpretations of ground deformation, and KML data were adapted to prevent potentially sensitive Navy Base information from being viewed by removing photographs and database fields other than the entity that collected the data.

### 8.2.9 Acknowledgements

People who participated in the collection effort and shared data with USGS and CGS include the following:

- **Arizona State University**: Williams, Alana; **California Geological Survey**: Burgess, Paul; Dawson, Timothy; DeFrisco, Michael; Frost, Erik; Graehl, Nicholas; Gutierrez, Carlos; Hernandez, Janis; Holland, Peter; Ladinsky, Tyler; Mareschal, Maxime; Morelan, Alex; Olson, Brian; Patton, Jason; Pridmore, Cynthia; Rosa, Carla; Roth, Nathaniel; O’Neal, Matt; Seitz, Gordon; Spangler, Eleanor; Swanson, Brian; Thomas, Kate; Treiman, Jerry; Zachariasen, Judith; **California Institute of Technology**: Avouac, Jean-Philippe; Padilla, Salena; **California State University, Fullerton**: Akciz, Sinan; **Desert Research Institute**: Bacun, Steven; **InfraTerra**: Hitchcock, Chris; Kozaci, Ozgur; **NASA Jet Propulsion Laboratory**: Milliner, Chris; **Pacific Gas & Electric**: Bachhuber, Jeff; Madugo, Chris; **Private Consultant**: Helms, John; **United States Geological Survey**: Angster, Steve; Bennett, Scott; Brooks, Ben; Delano, Jaime; DuRoss, Chris; Erikson, Todd; Gold, Ryan; Haddon, Beth; Hudnut, Ken; Kendrick, Katherine; McPhillips, Devin; Nevitt, Jose; Philibosian, Belle; Pickering, Alexandra; Ponti, Daniel; Scharer, Kate; Thompson Jobe, Jessica; **United States Navy**: Blake, Kelly; Bork, Stephan; **University of California, Davis**: Oskin, Mike; **University of Nevada, Reno**: Chupik, Colin; Koehler, Rich; Pierce, Ian; **University of Southern California**: Dolan, James; Hatem, Alex.

### 8.3 Clearinghouse Data Collection

*Contribute by Maggie Ortiz-Millan.*

Clearinghouse participants without a preferred data collection method to collect and share photos were encouraged to use the Fulcrum application on their smartphone. Earthquake Engineering Research Institute (EERI) has developed a reconnaissance data collection form within Fulcrum that covers several disciplinary topics, including buildings, lifelines, bridges, emergency response, liquefaction, landslide, fault rupture, and tsunami. More than 10 Clearinghouse participants submitted 59 records through the Fulcrum application (see Figure 72). The Fulcrum application is user-friendly and intuitive, and participants were able to successfully collect data after a short demonstration from Clearinghouse staff.
Figure 72. A total of 59 observations were recorded in Fulcrum by Clearinghouse participants.

The data collected through Fulcrum was synced to the Virtual Clearinghouse website, which allows users to view the data in the Clearinghouse photo gallery and on the ArcGIS Online data map on the Virtual Clearinghouse website (see Figures Figure 73 and Figure 74).

Figure 73. View of photos collected through the Fulcrum application in the Virtual Clearinghouse website photo gallery.
Figure 74. Screenshot of the Clearinghouse ArcGIS Online data map showing USGS ShakeMap for the 4 July 2019 M6.4 earthquake, location of reconnaissance observations submitted through Fulcrum, and the data table with observation details.

Data collected through Fulcrum can be downloaded as a keyhole markup language file, and photos and metadata can be downloaded through the photo gallery interface as a comma-separated values file with a corresponding zip file of photos.

8.4 GEER Data Collection and Products


Following the Ridgecrest Earthquake Sequence, consisting of an M6.4 foreshock and M7.1 mainshock along with many other smaller events, the National Science Foundation–funded Geotechnical Extreme Events Reconnaissance (GEER) Association, with cofunding from the B. John Garrick Institute for the Risk Sciences at University of California Los Angeles and support from the Southern California Earthquake Center, deployed a team to gather perishable data. The team focused their efforts on documenting ground deformations, including surface fault rupture south of the Naval Air Weapons Station China Lake (NAWSCL), and liquefaction features in Trona and Argus. The field reconnaissance efforts were organized into five missions conducted between 5 and 22 July 2019. Two of the missions involved ground-based measurements using digital cameras, global positioning system (GPS) trackers, tape measures, and rulers. Three of the missions involved unmanned aerial vehicles (UAVs) equipped with digital cameras to perform Structure from Motion (SfM) processing to obtain point clouds and digital surface models. A map showing the locations studied during these missions is provided in Figure 75. The GEER team released version 1 of their report on July 19 and version 2 on August 3 (Stewart et al., 2019). Furthermore, they published their experimental data under the following digital object identifiers: 10.17603/ds2-vpmv-5b34, 10.5967/5sq2-rs60, 10.17603/ds2-wfgc-a575, 10.17603/ds2-c5z3-wy42, and 10.17603/ds2-tyca-se83.
Figure 75. Map of the M6.4 (in blue) and M7.1 (in red) fault ruptures as given in Stewart et al. (2019), with shapefiles obtained from D. Ponti (17 July 2019) along with polygons flown during UAV missions. Reconnaissance efforts in this paper focused on the locations south of NAWSCL where the fault ruptures cross Highway 178, and liquefaction effects in Trona and Argus.

Ground-based reconnaissance missions are organized in DesignSafe (www.designsafe-ci.org; Rathje et al., 2017)\textsuperscript{39}, which is a cyber-infrastructure tool for the natural hazards community. Observations of earthquake effects were recorded using GPS trackers, digital cameras with GPS geotagging capabilities, and hand-held measuring devices, including tape measures and rulers. These observations are organized into collections consisting of GeoJSON files that organize each researcher’s track logs and photographs into a file format that can be viewed using the HazMapper tool in DesignSafe. An example view of a GeoJSON file viewed using the HazMapper tool is shown in Figure 76, including a photograph of a repaired water pipe that ruptured at the location where it crosses the M6.4 surface rupture. Each photograph appears as a thumbnail, and a reduced-resolution version of the photograph appears when a user clicks on the thumbnail. Full-resolution versions of the photographs are also available through DesignSafe. Data from the collections were synthesized into a QGIS project, and Figure 77 is an example showing the ground cracks at the location where the M6.4 surface rupture crosses Highway 178.
Figure 76. Visualization of "Brandenberg_July_6_2019.geojson" file using the HazMapper tool in DesignSafe.

Figure 77. Map showing locations of measured ground cracks where M6.4 fault rupture crosses highway 178 (Stewart et al., 2019).
The UAV missions produced digital photographs that were processed using SfM to obtain point clouds and digital surface models. The intention of these missions was to preserve information about the nature of the surface fault rupture and liquefaction effects before perishable data is lost to repair efforts, rainfall, and other effects. Figure 78 shows an SfM point cloud of Trona, California, where liquefaction and lateral spreading was observed. The Potree point cloud viewer in DesignSafe enables users to interact with the point cloud. Liquefied sand ejected from the subsurface flowed over the parking lot at the Family Dollar store (near left center of Figure 78), and sand boils are visible in the point cloud to the south of Highway 178 in the foreground of the image. Ground cracks and compressional features indicative of liquefaction-induced lateral spreading are also visible throughout the imaged area.

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8.5 JPL Structure from Motion Products

Contributed by Andrea Donnellan, Gregory Lyzenga, Jun Wang, Marlon Pierce, and Christine Goulet.

JPL began collecting repeated structure-from-motion (SfM) measurements using small uninhabited aerial systems (sUAS) five days after the mainshock, following guidance from Christine Goulet of the Southern California Earthquake Center. The objective was to collect repeated SfM data to observe post-earthquake behavior on sections of the M6.4 and M7.1 ruptures (Brandenberg et al, 2019; Donnellan et al., submitted; Ponti et al., in press)\textsuperscript{40,41,42}. An additional objective was to constrain the resolution of SfM data relative to subsets of ground-truth measurements for calibration of the subsequent
interpretation of surface displacements. Areas for each rupture were selected to be off and to the south of the China Lake Naval Air Weapons Station but on the main part of the rupture for each event. Areas targeted were roughly 500 m × 500 m to allow for locations on both ruptures to be observed in a day at high precision and wide enough to capture strains in the fault normal directions (see Figure 79).

![Diagram of surface displacements](image)

**Figure 79.** Top: Location of the two sites where structure from motion observations were carried out. Bottom: Products for the M6.4 rupture (left) and M7.1 rupture (right) showing mapped interpretation of cracking in blue.

We used Parrot Anafi vehicles, each with a 21 MP camera, and flew double grids at 45 m above ground level using Pix4DCapture. The camera angle was set to 75° from horizontal looking forward. The front overlap of the images was 80%, and the side overlap was 70%. We processed the data using Pix4D. The resulting ground sample distance of the products was about 1.5 cm. We surveyed ground control points (GCPs) at targets visible in the images using Septentrio APS-3G Global Navigation Satellite System (GNSS) base station and real-time kinematic rover. The base station broadcasts corrections to the rover for centimeter-level relative positioning of the targets. We processed the base station data using the National Geodetic Survey’s e-mail Opus processing system and adjusted the local network of GCPs into an absolute reference frame. Root mean square repeatability of the GCPs is ≤2 cm.
We posted the products to GeoGateway (http://geo-gateway.org) under the three-dimensional imaging tab. Products include digital surface models, orthomosaic images in tagged image file and KML formats, and point clouds. We collected data at both locations on 9 July 2019, 11 July 2019, 15 July 2019, 22 July 2019, 8 August 2019, and 27 September 2019 to date. The centimeter-level resolution of the images enabled identification of surface cracks using the high-resolution KML files in Google Earth. Additional fault splays have been identified using this method, including a conjugate splay at the M7.1 rupture that, to our knowledge, had not been field mapped. In addition to identifying surface cracking and coseismic changes, a goal was to measure postseismic motion over time. At present, we have not observed definitive postseismic displacements. Continued measurement over several years will show whether afterslip occurred on the fault ruptures, whether distributed deformation occurred across the survey areas, or whether postseismic deformation occurred more broadly than the survey areas.

Both scientific and practical lessons were learned from these field studies. The processed data may show some poroelastic response to the earthquake in the week following the events. We are not observing much fault afterslip. Results of postseismic deformation from GNSS stations more broadly distributed suggests that afterslip or relaxation is occurring deeper in the crust. Conducting these types of measurements at the rupture ends might show more postseismic deformation or elucidate how stress decays away from the rupture tip, such as measured by Donnellan et al. (2018)\textsuperscript{43} for the El Mayor-Cucapah earthquake. External validation of the GCPs with a local continuously operating GNSS station would also allow for better interpretation of vertical motions and overall horizontal motion of the scene. The sUAS and their associated batteries suffered from the high heat during the summer observations. The vehicles stopped writing data to the memory card after about five flights. We improved performance by keeping batteries in coolers, swapping vehicles between flights or locations, and cooling them between flights while we downloaded the data. Three flights are required to cover the M6.4 rupture study area and five flights minimum to cover the M7.1 rupture study area. Some vignetting or striping appears in the final product. This is typically because of degradation at the edge of the sensor. We have not seen this in previous surveys in other locations, so the degradation may be due to the extreme heat.

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10 REFERENCES


