ESi WHITE PAPER

July 4 & 5, 2019 Ridgecrest Earthquake Sequence

Observations from a Post-Earthquake Reconnaissance

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Summary

The Ridgecrest Earthquake sequence that started on July 4, 2019 ended a protracted quiet period for large earthquakes in California. The rupture continued a slow-moving pattern of large strike-slip earthquakes in the desert region of Southern California that began with the Landers earthquake in the early 1990s. The July 5, 2019, event was the largest earthquake to strike California in the past 20 years.

Following the earthquakes, a multidisciplinary team from ESi, an engineering consulting and forensic investigation firm, traveled to the affected region to make observations and document damages that resulted from the July 4 and 5 events. This report summarizes the findings from our one-day visit to the Ridgecrest area on July 9, 2019.

While the scale and severity of the damage observed by ESi personnel in publicly accessible areas did not rival that of other major earthquakes of recent memory, i.e., the 1989 Loma Prieta and 1994 Northridge Earthquakes, it is understood that major damage did occur at the Naval Weapons Station at China Lake. These findings of our reconnaissance highlight the important roles played by the details of the event, including earthquake magnitude, style and proximity, the type and age of construction, and the local soil and groundwater conditions.

End of a 20-Year Seismically Quiet Period

The ESi Southern California office organized a reconnaissance to the areas affected by the Ridgecrest earthquake sequence that included the July 4, 2019, magnitude 6.4 and July 5, 2019, magnitude 7.1 events.[1]

The second of these events was the largest earthquake to strike California in the past 20 years, and was felt strongly across the southwest, including cities as far away as Las Vegas, Nevada; Phoenix, Arizona; and San Diego, California. The areas most immediately affected by these events include the Mojave Desert communities of Ridgecrest and Trona, California, as well as the Naval Air Weapons Station China Lake, California.

The July 5 earthquake was strongly felt at the ESi Southern California office, located about 170 miles south of the epicenter. At this distance, the greatest impacts came in the form of water being sloshed from innumerable swimming pools in the area.

On July 9, armed with cameras and field equipment, a multidisciplinary team of ESi professionals embarked on a day-long damage assessment of the epicentral area. Personnel participating in the field assessment included Kristina Cydzik (civil engineering), Philip Shaller (engineering geology), and Macan Doroudian (geotechnical engineering) from the ESi Southern California office, as well as Jennifer Jirschefske (structural engineering), who was visiting from the ESi Colorado Springs, Colorado office.

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[1] The magnitude of the earthquakes reported herein is the so- called "Moment magnitude," a measure of earthquake size in terms of the amount of energy released. It is subsequently abbreviated in this report using the nomenclature "M" followed by a number that represents the logarithm of the energy released in an earthquake. Specifically, moment magnitude relates to the amount of movement by rock (i.e. the distance of movement along a fault or fracture) and the area of the fault or fracture surface. Since moment magnitude can describe something physical about the event, calculated values are easily compared to magnitude values for other events. The higher the number, the more energy is released during an earthquake event. For additional details of the computation methodology, the reader is referred to the USGS Earthquake Glossary: https://www.usgs.gov/faqs/moment-magnitude-richter-scale-what-are-different-magnitude-scales-and-why-are-there-so-many?qt-news_science_products=0#qt-news_science_products

Figure 1. ESi earthquake reconnaissance team. From left to right: Cydzik, Shaller (back to camera), Jirschefske, and Doroudian.

Despite the magnitude of the events and the recorded intensity of ground shaking, residential and commercial damage in the epicentral region was relatively modest when compared to historical events of comparable magnitude (e.g., the 1989 M6.9 Loma Prieta Earthquake or the 1994 M6.7 Northridge Earthquake).

The town of Trona experienced the most extensive damage among the areas visited, as a result of older construction in combination with significant manifestations of ground deformation (liquefaction and lateral spreading).

ESi's reconnaissance documented road, railroad, utility, and structural damages at industrial, commercial, and residential properties in Trona, as well assubstantial ground rupture associated with the causative faults along State Highway 178 connecting Trona and Ridgecrest.

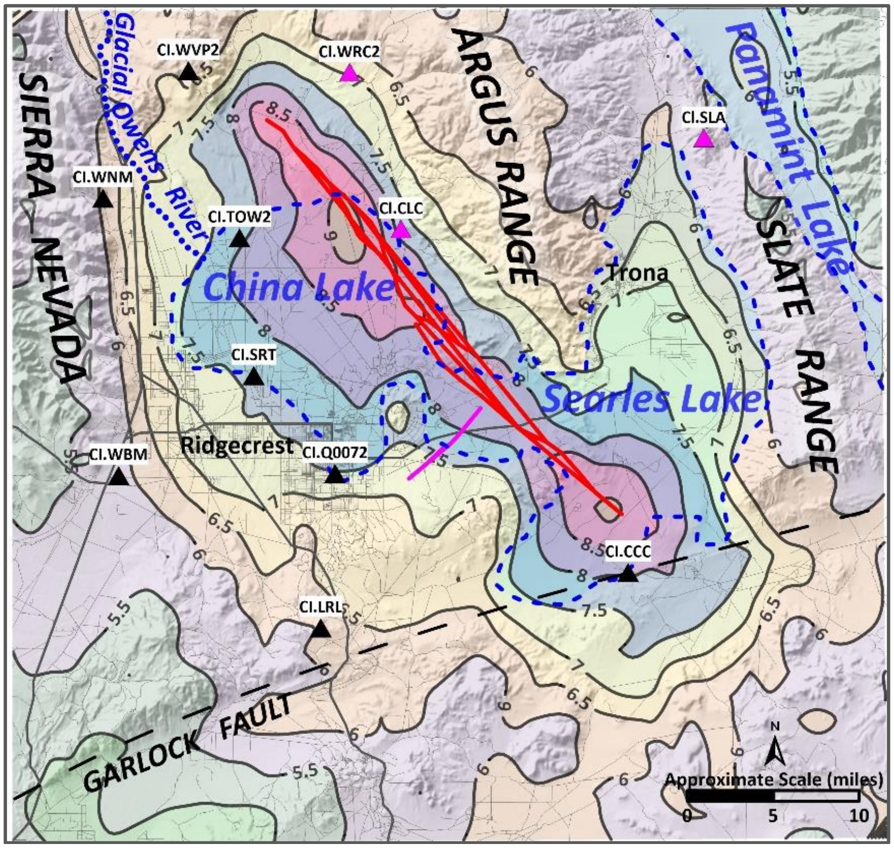

Figure 2 Map showing estimated peak intensity of the Ridgecrest M7.1 main shock. Ground rupture associated with the main shock is shown by red lines; the rupture plane of the M6.4 foreshock is shown by the pink line. The peak intensities are calculated from ground shaking levels measured at seismic stations throughout the region (black and pink triangles). All the seismic stations shown were functioning during the July 4 foreshock, but the three pink stations were inoperative at the time of the July 5 main shock. USGS data obtained August 19, 2019.

Ground shaking intensity maps such as the one in Figure 2 show an estimate of the *effects* of an earthquake at a given location, as opposed to the earthquake's inherent *force* or *strength*. During the 20th Century, maps like this were generated based on reports of damage and other effects made by persons in the affected region. Today, the data used to construct these maps are automatically generated by the USGS within minutes of the causative earthquake, with the intention of providing first responders a road map to potential areas of focused damage. These data are based on ground accelerations recorded by seismic stations in the affected area, the generalized geology of the local area, and the fault rupture style and direction.

Note that the highest estimated intensity levels in the vicinity of the M7.1 main shock corresponded to the basins of China and Searles Lakes (near the ends of the causative fault), while the greatest damage in the earthquake sequence occurred in Trona and on the grounds of the Naval Weapons Station China Lake (located just northeast of Ridgecrest). Though intensity maps such as these provide a good starting point for first responders seeking damage and casualties after an earthquake, they do not reflect the actual damage sustained in the event as did the previous generations of intensity maps.

The ESi earthquake reconnaissance team observed a wide variety of earthquake-related structural, geotechnical, and geological features in the epicentral region. The following vignettes document some of the lessons learned from our day-long excursion.

Land of Fire and Ice…

The Ridgecrest earthquake sequence took place in an area known more for its ice age history than for its earthquakes. In their heyday during the last ice age, China Lake and Searles Lake formed part of a chain of lakes and streams fed by glacial runoff from the Sierra Nevada Mountains. Other water bodies in this system included Owens Lake, Panamint Lake, and Lake Manly, which occupied Death Valley during much of this period. It's hard to believe now, but at its peak, Searles Lake measured over 600 feet deep! Today, the dry lakes are generally uninviting places to visit, a notion reinforced by colorful place names like "Poison Canyon."

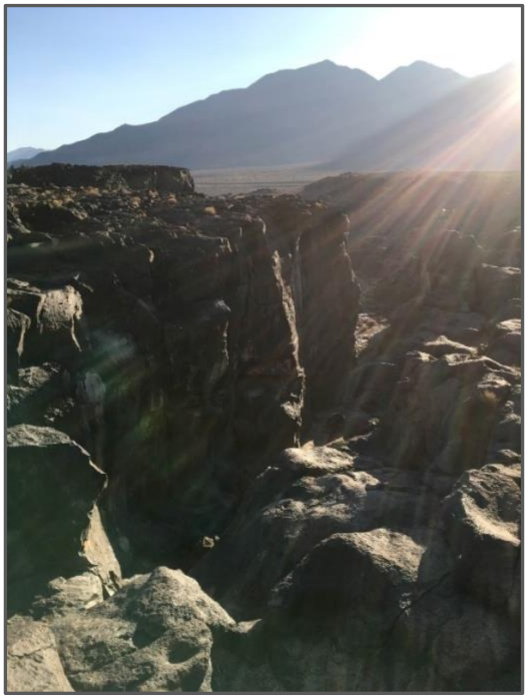

Figure 3. Photo of "Fossil Falls," a gorge cut through ice-age era lava flows by glacial runoff at the south end of the Owens Valley (foreground, framed by the southern Sierra Nevada mountains in the distance). Glacial runoff that passed through this gorge filled China Lake, Searles Lake, and other major lakes during recent ice ages. This area lies about 10 miles northwest of the Ridgecrest earthquake rupture.

The most intriguing feature of the landscape in the epicentral region are several clusters of tufa pinnacles that stand sentinel at the southerly end of Searles Lake (see Figure 4). These odd features formed as a result of groundwater seepage into the lakes during one or more high stands of the lake, and thus represent an interesting relic of glacial time.


Photo courtesy A.L. Shaller, used by permission

Figure 4. Overview of the tufa pinnacles in Searles Lake.

In addition to the ancient lake beds, the northwestern tip of the M7.1 earthquake came close to touching another important ice age feature of the region: the Coso Volcanic Field, an area that has experienced at least 40 eruptions over the past 250,000 years.

The youngest representative of this field is Red Hill, a conspicuous cinder cone located just off Highway 395 near Little Lake. The cone is a well-known landmark to those traveling between Los Angeles and Mammoth Mountain for their weekend outdoor adventures or ski trips. Red Hill is generally thought to be only about 10,000 to 20,000 years old, an infant by geologic standards. Will the recent earthquake result in a renewal of volcanic activity in the area? Only time will tell.

The Usual Suspects

Much of the damage observed in the epicentral region occurred in the old company town of Trona. The principal industry in Trona is chemical production, consisting of borax, boric acid, and soda ash extracted from brines pumped from beneath the (mostly) dry bed of Searles Lake. The boron in the borax minerals originated in volcanic deposits in the upper Owens Valley. These chemicals were carried to the lake in solution, to be concentrated in its salt pan when the lake finally dried up, a process repeated many times over the lake's long history. Commercial salt extraction from Searles Lake commenced in the 1860s and has continued off and on ever since. As a result of Trona's long history, a lot of older structures are present in and around town, some of which appear abandoned and/or disused.

The most obvious structural damage observed in Trona affected unreinforced (or insufficiently reinforced) concrete masonry unit (CMU) walls. Of the failed CMU walls observed, all were only partially grouted and only a few reinforced. Where the walls were reinforced, the reinforcement consisted of plain (undeformed) rebar. Plain rebar is smooth and therefore creates a poor mechanical bond between the bar and the surrounding grout. This condition reduces the tensile capacity of the section and makes the section less capable of resisting overturning forces. This quality of rebar is representative of the era of construction. Since the 1950s, the use of plain rebar has been phased out of new construction in the U.S.

Of the observed partially grouted walls, some cells exhibited vertically placed grout, while others contained no horizontal reinforcement (see Figures 5 and 6). In those cases where horizontal reinforcement was installed, a lack of adequate splice and development length reduced its effectiveness. For these reasons, the horizontal reinforcement failed to tie the grouted cells together contributing to numerous wall failures in Trona.

Figure 5. Damaged block wall observed in Trona. The cells within the blocks were neither filled with grout nor reinforced with rebar.

Figure 6. Damaged block wall observed in Trona. The cells within the blocks were neither filled with grout nor reinforced with rebar.

Figure 7. The chimney of this home collapsed and fell through the roof of the structure.

Numerous brick chimneys on the roofs of residential homes also experienced damage during the Ridgecrest earthquake sequence. An example is shown in Figure 7. Brick chimneys are not typically reinforced, so the mortar between the bricks is the only thing holding the bricks together. Because chimneys are located at the tops of buildings, they are prone to higher lateral accelerations (as you move higher on a structure, accelerations increase). The acceleration, coupled with the heavy mass of a brick chimney, creates a large lateral force on the chimney.

These forces can cause the mortar to fail and allow the chimney to collapse. In several instances, the impact from the collapsed brick also caused the roof area around the chimney to fail.

Figure 8. A displaced chimney cap at the top of the smokestack at the Searles Valley Minerals facility in Trona (right side of photo)..

One of two smokestacks located on the Searles Valley Minerals facility in Trona also experienced damage in the form of a displaced chimney cap (see Figure 8). Similar to the collapsed residential chimneys, the top of the smokestack experienced higher lateral accelerations from the ground shaking. This type of damage is not particularly surprising in an area affected by a significant earthquake.

Cylindrical steel water tanks are prone to earthquake damage, especially when full or partially full of water. In the Ridgecrest earthquake area, ESi's reconnaissance team observed one such damaged structure along State Route 178 between Trona and Ridgecrest (see Figures 10 and 11).

The water tank exhibited buckling at the base (also known as an "elephant foot" failure). The liquid inside the tank and the flexibility of the tank walls tends to amplify the overturning forces on the tank. The side of the tank that is in compression buckles and bulges out when the compression capacity of the tank wall is exceeded. The ground shaking also resulted in the failure of the pipe connection on the opposite side of the tank, resulting in uncontrolled drainage of the tank.

Of course, ground conditions also make a big difference in how a building performs when subjected to an earthquake…

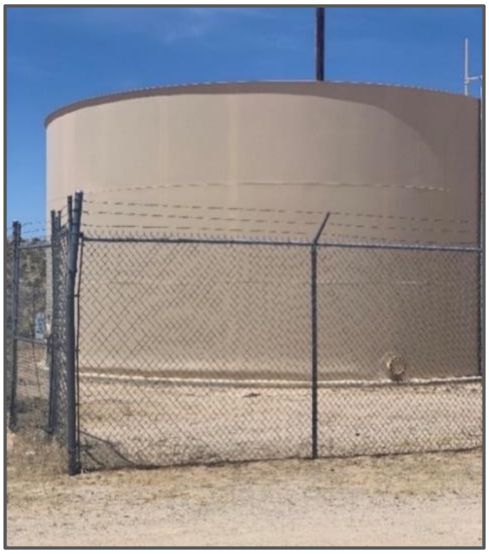

Figure 9. Evidence of an elephant foot failure at the bottom of this water tank located along State Route 178.

Figure 10. A pipe rupture caused water to uncontrollably flow from the tank. Evidence of the flow path is present on the right side of this photo.

Who Could Complain About Water in the Desert?

In addition to the cited structural issues, shallow groundwater conditions present near the shore of Searles Lake also contributed to the damage observed in Trona. These conditions facilitated liquefaction and lateral spreading during one or both of the earthquakes. Liquefaction of saturated soils is a complex business, but generally requires a combination of loose soils and prolonged ground shaking in the presence of a shallow groundwater table. Liquefaction of soils is generally associated with larger earthquakes (i.e., M5 and greater), mainly because the process is contingent on the soil column experiencing numerous load cycles, which incrementally increase pore pressures in the soil until liquefaction is achieved. The number of load cycles is a function of the duration of ground shaking, and the duration of ground shaking generally increases with earthquake magnitude.

Figure 11. Sand boils observed along the shoulder of State Route 178 within the Trona city limits. Sand boils are a common surface manifestation of liquefaction.

Figure 12. Lateral spreads often accompany ground liquefaction. This phenomenon occurs when drier surficial soils migrate downhill over a liquefied substrate. The spreading can take place on slopes as mild as one degree; in Trona, the affected areas slope about three degrees towards the lake (arrows showing the direction of movement).

Lateral spreading affected the infrastructure in Trona in numerous ways, including damaging streets and sidewalks, shattering buried sewer and water lines, and destabilizing power poles. Liquefaction-induced lateral spreading also caused slab-on-grade foundations to crack. Figures 12 through 14 show examples of the damage that resulted from lateral spreading in Trona.

Figure 13. Lateral spreading in Trona caused damage to the foundation of this home. Ground movement occurred from left to right in this image.

Figure 14. Cracks in the asphalt roadway resulted from some of the instances of lateral spreading that occurred in Trona.

All Earthquakes (and All Structures) are NOT Created Equal

In the locations visited, the performance of the built environment in this earthquake departed notably from some past large earthquakes in California (particularly the 1989 Loma Prieta and 1994 Northridge events). Structures in the city of Ridgecrest performed quite well despite being located very close to the epicenters of both the July 4 and July 5 earthquakes and experiencing estimated Mercalli Index ground shaking intensities greater than 7. To understand the differences in damage patterns observed between different events, we must consider the types of structures that were present in these areas, the soil conditions in the affected areas, the nature of the earthquake events, and the locations of the developed areas relative to the causative faults.

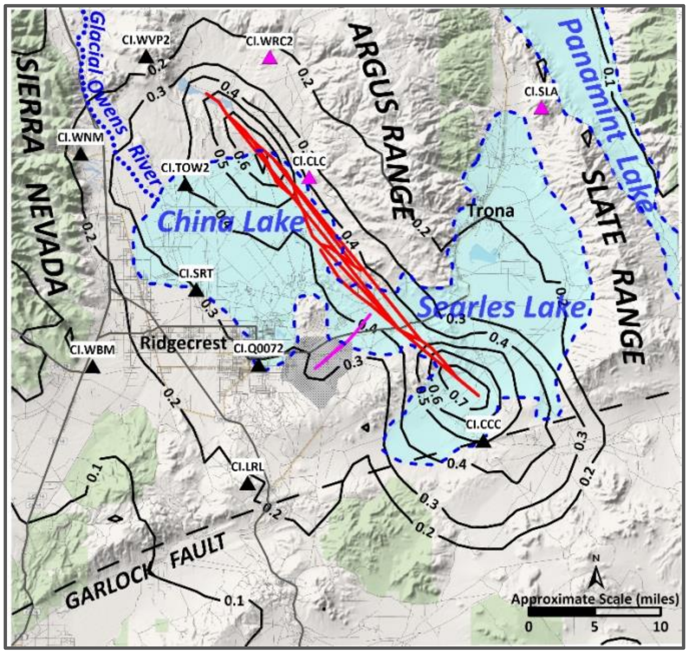

Figure 15 Map showing consolidated peak ground acceleration (in fractions of g, gravitational acceleration) of the two principal earthquakes in the Ridgecrest seismic sequence. The rupture plane of the M6.4 foreshock is shown by the pink line. Ground rupture associated with the M7.1 main shock is shown by red lines. Locations of seismic stations are shown by black and pink triangles. Areas where peak ground acceleration was controlled by the foreshock are indicated by gray shading, which includes eastern outskirts of Ridgecrest. USGS data obtained August 19, 2019.

The extent of structural damage in the Loma Prieta and Northridge Earthquakes was closely related to the significant number of soft-story and non-ductile concrete structures present in the affected areas. As a result, these types of structures gained a reputation for poor structural performance during seismic events that provided little to no warning prior to collapse.

Why was Ridgecrest spared significant damage? Many structures in Ridgecrest and Trona are single-story or two-story wood framed structures. Few soft-story or non-ductile concrete buildings were observed in these communities. Single-story or two-story wood framed buildings behave very differently from soft-story and non-ductile concrete structures when subjected to lateral loads. The shear walls and stucco finishes in such buildings provide the stiffness needed to prevent collapse, while the flexibility in the wood members and nailed connections allow the structures to dampen the lateral forces that the buildings experienced during the earthquake. This is not to say that wood framed structures are indestructible; they are just somewhat less vulnerable to ground accelerations than soft-story or non-ductile concrete frames.

Ground conditions are also relevant to the damage sustained in an earthquake. Much of the worst damage in the Loma Prieta Earthquake took place in areas underlain by soft, poorly consolidated soils, which resulted in longer and more severe shaking at those locations. This issue may also have played out in Trona, which also appears to be built on soft soils. In San Francisco, the soft soil conditions were associated with soft bay mud and poorly compacted fill materials. In Trona, the soft soils consisted of geologically recent lake deposits. Ridgecrest, in contrast, was built on alluvial deposits that generally perform better in seismic events than these softer lake deposits, for the same level of shaking. As shown on the image below, estimated ground accelerations are highest on the beds of China Lake and Searles Lake and substantially lower in areas of exposed bedrock, such in the Slate, Argus, and Sierra Nevada Mountain Ranges.

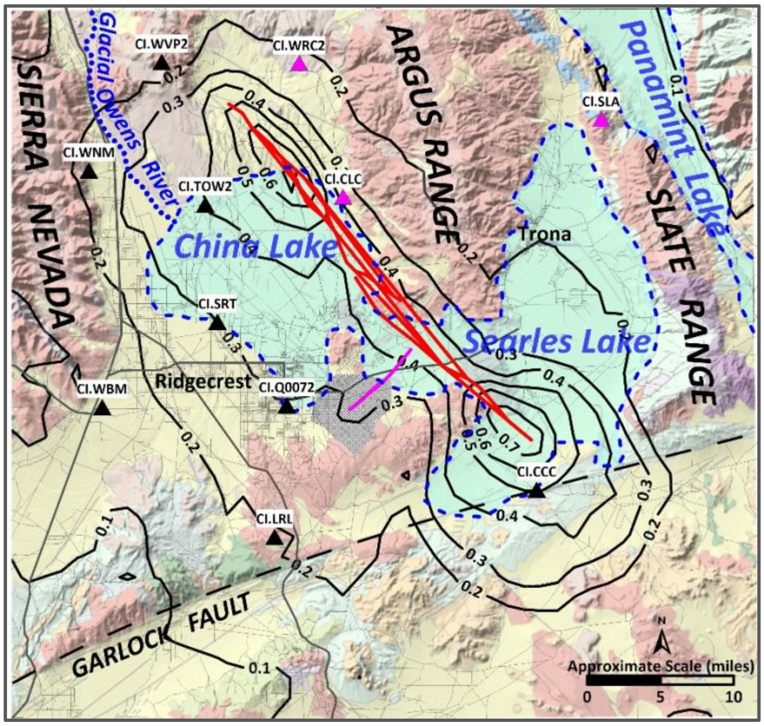

Figure 16. Map showing consolidated peak ground acceleration (in fractions of g, gravitational acceleration) of the two principal earthquakes in the Ridgecrest seismic sequence. The rupture plane of the M6.4 foreshock is shown by the pink line. Ground rupture associated with the M7.1 main shock is shown by red lines. Areas where peak ground acceleration was controlled by the foreshock are indicated by gray shading. Yellow shaded areas are underlain by alluvium and lake sediments. Red, light blue, and purple shaded areas are underlain by bedrock materials such as granite and slate. USGS data obtained August 19, 2019.

A third factor at work in the contrasting damage patterns of these earthquakes was the nature of the associated fault ruptures. The Northridge Earthquake took place on a blind thrust fault (in which a significant component of the fault motion is in a vertical direction) that experienced very rapid displacement and a highly directional impulse force, resulting in very high peak ground accelerations and the fastest peak ground velocity ever recorded. These conditions are very challenging to the built environment. The Ridgecrest earthquake sequence, by comparison, took place on strike-slip faults that generated peak much lower ground accelerations than the maximum values reached in the Northridge blind thrust event.

Sometimes You Just Have to Get Lucky

The highest intensity ground shaking in the Ridgecrest Earthquake sequence affected the sparsely inhabited lakebed areas north and southeast of Ridgecrest. By comparison, the Northridge Earthquake took place directly beneath the densely built San Fernando Valley. As such, there were an abundance of structures in the areas that experienced the highest intensity ground shaking and hence many more opportunities for structures to be damaged in the 1994 event.

The ESi team did not have access to the facilities on the Naval Weapons Station China Lake during the field reconnaissance. News reports as of August 15, 2019 state that the facility incurred over $5 billion in damage in the earthquake sequence. Based on the very modest levels of damage observed in Ridgecrest, this high dollar figure seems likely to be associated with damage to advanced and/or sensitive facilities and equipment on the base that likely have no counterpart in the neighboring commercial and residential areas. It is noted, however, that the base lies in the lakebed area north of Ridgecrest and therefore: 1) is likely underlain by soft soils, resulting in ground motion amplification, 2) was subjected to large magnitude ground surface ruptures, and 3) experienced among the highest inferred levels of ground shaking incurred during the earthquake sequence. The base therefore likely experienced earthquake-related effects much more challenging to the built environment than those experienced in nearby Ridgecrest.

Long Live the Field Act!

The Field Act of 1933 represents one of the first pieces of legislation in the United States to mandate earthquake-resistant construction. The California State Legislature passed the Act, applicable to the construction of new public schools in the State of California, in response to excessive damage sustained by school buildings in the M6.3 Long Beach earthquake that struck earlier that year. Since 1940, no Field Act compliant building has collapsed under seismic load and no students have been seriously injured or killed in a Field Act compliant building.

Photo credit: A.L. Shaller, used by permission

Figure 17. The concrete sidewalk in front of Trona High School showed evidence of lateral spreading.

Figure 18. The concrete sidewalk in front of Trona High School showed evidence of lateral spreading.

The commendable performance of Trona High School (built in 1941) highlights the continuing benefits derived from the landmark 1930s legislation. Despite ground shaking intensities of 6 to 7, ground accelerations of about 0.2 g (about 20 percent as high as the acceleration of gravity), and obvious indications of lateral spreading adjacent to the structure, the original school building apparently performed well in the earthquake sequence.

Today, provisions of the Field Act are extended to include requirements for specialized licensure for engineering professionals engaged in the design of critical structures in California: The Structural Engineer license (SE), Geotechnical Engineer license (GE), and the Certified Engineering Geologist license (CEG). The critical structures covered by these special licenses include schools, hospitals, cell towers, care facilities, fire stations, and police stations. The ESi earthquake inspection team included three experts holding these specialized licenses: Jenny Jirschefske (SE), Macan Doroudian (GE), and Philip Shaller (CEG).

The Watched Pot…

When it comes to earthquakes, people should probably come to expect the unexpected. When was the last time an earthquake actually occurred at a place and time that anyone anticipated?

The July 4 – 5, 2019 Ridgecrest earthquake sequence took place in an area not known for its vigorous historical seismic activity. In fact, the surface rupture of the M7.1 main shock didn't even follow the alignment of any known mapped fault! Prevailing wisdom suggests that major earthquakes should occur in areas with active faults (i.e., those that have been active in the past 10,000 years), and that active faults usually leave a strong mark on the landscape. Preliminary assessment of the trace of the Ridgecrest fault shows it crossing undeformed dry washes and lake shorelines, some of which may be in excess of 100,000 years old. This lack of geomorphic evidence of past faulting suggests that the Ridgecrest earthquake sequence represented a very rare and unusual event.

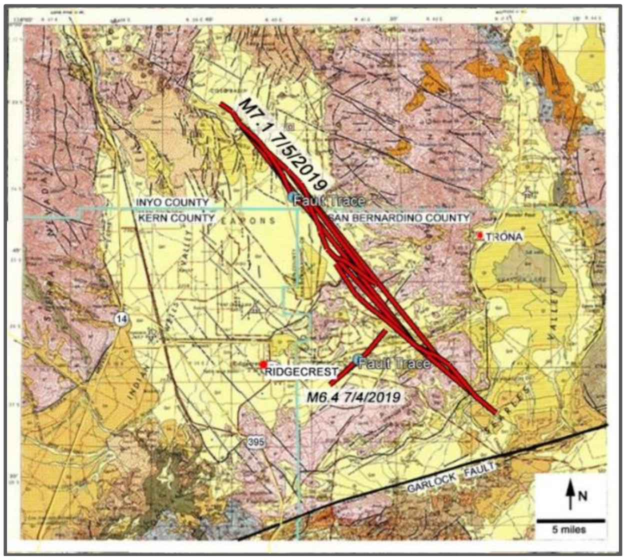

Figure 19 Geologic map of the Ridgecrest area showing the fault rupture associated with the M6.4 foreshock and the M7.1 main shock (red lines). The locations of previously mapped faults are shown by black lines. Except for some nearby discontinuous fault segments, no throughgoing fault had previously been mapped in the area (base map California Division of Mines and Geology, 1962, Geologic map of California, Trona Sheet, scale 1:250,000).

Roads, Pipelines, and Railroads

The comforts of daily living are frequently challenged by major earthquake events due to damage to utility and transportation infrastructure. Indeed, damages to systems such as these are an important driver for the recommendations geared toward household earthquake preparedness. Both the M6.4 and M7.1 Ridgecrest events caused damage to drinking water pipelines, sanitary sewers, and electrical lines by way of fault rupture and lateral spreading. Road damages accompanied both of the events, but were rapidly repaired such that scant evidence remained by the time of our July 9 site inspection. In contrast, water and sewer lines were still in the process of being repaired during our reconnaissance. County and State emergency services as well as the National Guard stationed in the City of Trona operated a response center offering bottled water, access to portable showers and toilets, and other supplies.

In addition to road and pipeline damages, a private railroad line owned by Searles Valley Minerals also suffered damage, as evidenced by lateral spreading in the railroad embankment, disturbed ballast, and misalignment of the rails.

Figure 20. Emergency operations center organized outside of Trona High School.

Figure 21. Private railroad line damage.

Figure 22. New water pipe segments stockpiled near one of the ruptured pipelines.

Figure 23. Evidence of scour downslope from one of the ruptured water lines along Highway 178.

Figure 24. View of the repairs underway in a trench excavated to access the water and sewer lines severed by lateral spreading during the earthquake sequence.

Photo credit: A.L. Shaller, used by permission

Figure 25. Photo of the repairs underway to restore the water and sewer lines severed during the earthquake sequence. Note saturated condition of soil in excavator bucket.

Who Says Water Never Flows Uphill?

The Ridgecrest earthquakes provided us with a prime example of the significant landscape changes that can accompany large seismic events. The lateral and horizontal offsets caused by the surface ruptures not only changed the grades of roadways but also caused changes in the alignment of at least one ephemeral channel and a large watershed area in the fault zone. Alongside Highway 178, the ESi reconnaissance team found a scarp with an ~18 inch drop and an ~18 inch right-lateral strike-slip[2] offset, resulting in the misalignment of at least one pre-earthquake channel invert that will cause a diversion of runoff in future storms. Although an 18-inch fault displacement sounds large, the fault experienced as much as 8 feet of offset on portions of the Naval base. Much larger single-event fault offsets have been recorded on other fault lines in the past; as much as 40 feet (horizontally) along the San Andreas fault in Central California and 20 feet (vertically) along the Owens Valley fault zone, as an example. Displacements of this magnitude leave long-lasting scars on the landscape that affect drainage patterns for generations. For example, the cited vertical offset along the Owens Valley fault zone, which accompanied the great 1872 Lone Pine earthquake, created a graben (i.e., an elongated, fault-bounded depression) that filled with spring water, forming Diaz Lake which is located on the south side of the town of Lone Pine off Highway 395. Today, the lake is a popular recreational area, with boating, fishing, water sports, picnic grounds, camping, and trails. Earthquakes can certainly destroy, but they can also create new and attractive landscapes that can be enjoyed for generations to come!

Figure 26 View to the northeast along the flowline of a narrow channel offset ~18 inches vertically and horizontally by the fault scarp of the July 5 M7.1 earthquake. The two measuring staffs mark the offset sides of the channel invert.

Conclusion

The Ridgecrest earthquake sequence ended a 20-year quiet period for large earthquakes in California. The rupture continued a pattern of large strike-slip earthquakes in the desert region of Southern California that began in the early 1990s. The observed infrastructure damage was generally consistent with the age of

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[2] A strike-slip fault is a vertical fracture along which horizontal displacement has taken place. If the block opposite an observer looking across the fault moves to the right, the slip style is termed right lateral; if the block moves to the left, the motion is termed left lateral.

construction and proximity to the causative faults, with damage being exacerbated in Trona due to liquefaction and lateral spread near the shoreline of Searles Lake. The principal damage to the built environment apparently took place within the limits of the Naval Weapons Station China Lake, a facility constructed atop soft lakebed soils that straddled the ground rupture associated with the M7.1 main shock. The Ridgecrest Earthquake sequence was a rare and unusual event that underscores the complexity of assessing seismic hazards in the Golden State.

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