Ridgecrest Earthquake Sequence: Science Findings and Lessons

Seismology

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Thursday March 5, 2:30 – 3pm
NEC 2020
Seismic Temporary Deployments

- USGS coordinated
- On-base
- Deployed 7-19 July, until ~January 2020

Mc ~0.4 with this network compared to ~1.0 catalog Mc

Increased detail of fault/source information

*Cochran et al., SRL, 2020*

Cochran, Wolin, McNamara, Yong, Wilson, Alvarez, van der Elst, McClain, Steidl
Rufus Catchings and group @USGS
461 nodal instruments deployed
~July7 for a month
Grid + dense fault-crossing arrays
~ 30,000 M≥1 events
Focused on velocity structure, fault structure, damage zone

*Catchings et al., 2020*
Abhi Ghosh @ UCR deployed ~25 stations between July 6 and 23.

Surrounding the base
Still running
• **gmprocess** software developed at USGS
• **M7.1, M6.4**
• ~150 aftershocks
• M3+
• ~900 permanent stations
• Distances to 400km

Allows for rapid analysis of ground motion characteristics

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“why was there relatively little damage?”

Rich data set, co-located events of M3-7.1, what can we learn?

- relatively “well behaved”, no strong outliers
- But some interesting features: LA amplification? Non-linear (damping) behavior?

Near-field intensities

“why was there relatively little damage?”

Near field intensities and instrumental ground motion were average to slightly lower than typical + some non-linear site response

Non-linearity: low-Vs30 (soft) sites with large ground motions deamplify due to non-linear behavior

Existing (ergodic) models work well for ensemble data, on average... but not for every site

Parker et al. (2020) BSSA Special Issue
Hints of directivity, but not strong.

Consistent with other studies. Slow rupture speed?

Figure 6. 2.0s PSA $\varepsilon_{ij}$ as a proxy for directivity effects for M6.4 (left) and M7.1 (right) earthquakes. (Parker et. al)

Parker et al. (2020) BSSA Special Issue
Path/Site: Basin effects

Relatively less amplification in San Bernardino basin, contrary to ShakeOut scenarios. Source azimuth dependence of basin amplification:
- ShakeOut waves guided along the SAF; Ridgecrest waves traveling perpendicular.
- Azimuthal dependence also in Seattle basin (Wirth et al., 2019).
- Compare to off-shore San Clemente island.

Parker et al. (2020) BSSA Special Issue
Aftershock relocations

Shelly, SRL 2020
Lack of seismicity?

No. Local borehole network reveals similar post-Ridgecrest enhanced levels of seismicity in Coso.

But shallow brittle-ductile transition in Coso prevents moderate magnitudes.

Similar “lack of seismicity” observations post-1992 Landers may have suffered from similar incomplete sampling.
• Combined static stress change from M6.4 foreshock and M7.1 mainshock, source model of Liu et al. (GRL, 2019).

• Off-fault aftershock clusters fall mainly within the lobes of positive stress change:
  • to NW in the Olancha area
  • to SW in Garlock step-over
  • to NE near Panamint Valley (more diffuse and not completely in lobe)

Hardebeck (2020) BSSA Ridgecrest special issue.
Coseismic Slip inversion

$M_0 = 4.7 \times 10^{19}$ Nm

Factors resulting in low rupture velocity
- Low seismic velocity ($v_r \sim 0.8 \times V_s$)
- Propagation through viscous material with unusually high fracture energy (Scholz, 2019)
- Energy is dissipated in secondary faulting, e.g., off-fault plasticity (Gabriel et al., 2013)
Dynamic rupture modeling
4 separate sub events with “normal” rupture velocity but delayed starts
Match distinct pulses well at seismic, GNSS, strain stations
No need for slow rupture velocity

Hirakawa, E. and A. Barbour (2020), Kinematic Rupture and 3D Wave Propagation Simulations of the 2019 Mw 7.1 Ridgecrest Earthquake, BSSA.
USGS Aftershock Forecast

- USGS publicly released aftershock forecasts with frequent updates.
- Based on Reasenberg and Jones (Science, 1989). Updates adapted to sequence.
- Highest probability of triggering a large earthquake immediately following M6.4 and M7.1, then decays rapidly.
- Just before the M7.1, we had forecast a 1 in 200 chance of a magnitude 7 or greater in the next week. ~10,000 times the usual probability of an earthquake this size near Ridgecrest.
• Observed number of magnitude 3+ aftershocks usually close to the forecasted range, but with some fluctuation between under- and over-prediction.

• Lesson learned: the Reasenberg and Jones statistical model, which assumes all aftershocks were caused by the mainshock, is too simple for this complex sequence.

• We are switching to the epidemic-type aftershock sequence (ETAS) model that includes more complexity from secondary triggering. The ETAS model is currently being used to forecast the Southwest Puerto Rico sequence.
Station CCC MMI IX ~20 seconds after origin time

~10 seconds after MMI V GM alert

California strike slip earthquake can give long warning times for high ground motion in limited, specific cases when you’re in the right spot for amplifications (directivity, site amps, etc) and that’s where EEW can be useful.

GM variability is not all right away or near epicenter.

Chung et al. (2020) BSSA Special Issue
Scientific lessons learned / outstanding questions

- GM models generally worked well.
  Near-field GM and intensities showed slightly less GM than predicted, perhaps some non-linearity?
  Basin effects clearly evident. Azimuthal dependence?
  Still not enough strong GM records to test site response models for large GMs.

- Slow rupture velocity or delayed subevents? Lack of strong directivity. Multiple models for rupture velocity (as always, disagreement!)

- Coso – value of partnerships to acquire borehole (etc) data to give a complete picture of seismicity and earth structure. How do geothermal fields respond to larger nearby events?

- Aftershock Forecasting: Reasenberg and Jones statistical model, which assumes all aftershocks were caused by the mainshock, is too simple for this complex sequence \(\rightarrow\) switch to ETAS, currently used to forecast the Puerto Rico sequence.
• Scientific insights can drive the response.
• Rapid ground motion and aftershock data characterization helps quickly understand the event, where damage is, where to place temporary stations
• Develop scientific partnerships/relationships in quiet times so we can achieve the above quickly.
• Deployments:
  • Getting out there is important. We need technical help and maintenance of instruments!
  • Coordination between groups – response planning
  • Involve community in the process, talk to people/landowners, explain earthquakes, science first, not just there to get the data and get out. Understand you’re there for doing science.
  • Building and maintaining relationship, community.


Hirakawa, E. and A. Barbour (2020), Kinematic Rupture and 3D Wave Propagation Simulations of the 2019 Mw 7.1 Ridgecrest Earthquake, BSSA Special Issue


Pollitz, Fred. F., Jessica R. Murray, Jerry L. Svarc, Charles Wicks, Evelyn Roeloffs, Sarah E. Minson, Katherine Scharer, Katherine Kendrick, Ken Hudnut, Johanna Nevitt, Benjamin A. Brooks, and Dave Mencin, BSSA Special Issue
