Project Abstract
Earthquake moment tensor catalog in the Southern California has been routinely processed by the Southern California Earthquake Data Center (SCEDC) using a simple 1D Earth velocity model, which may introduce large uncertainties as the complicated Earth 3D structure effects cannot be adequately quantified. To establish the best practices of earthquake moment tensor catalog in the Southern California, we propose to adopt the Southern California Earthquake Center (SCEC) 3D Community Velocity Models (CVMs) in near-real-time automatic earthquake moment tensor inversion. Our study will result in a new moment tensor catalog for the Southern California region, and provide more accurate moment tensor solutions, focal depths, and moment magnitudes. Our catalog will be available for further seismological and geological investigations, and will contribute to mitigating the seismic hazard and risk in the area.

Intellectual Merit
We have developed a highly automated and efficient algorithm to determine the moment tensor solutions for small-to-medium-sized earthquakes using 3D velocity models in the Los Angeles region. Our results show that incorporating the 3D velocity model can refine the existing moment tensor catalogs in the region, resulting in more accurate focal mechanism solutions, focal depth, and moment magnitude. In addition, our highly accurate, efficient, and automatic inversion approach can be expanded in other regions and can be easily implemented in near real-time system.

Broader Impacts
The moment tensor catalog we produced will be the first regional scale catalog produced by full waveform inversions using 3D Green’s functions. The catalog can be used in estimating crustal stress state, fault geometries, and fault damages.

Exemplary Figure
Figure 6. Comparison of 66 example focal mechanisms from the 2019 Ridgecrest earthquake sequence between our solution (red), the HASH solution (black), and the SCEDC-CMT solution (blue). These three different solutions are mostly consistent.
Earthquake moment tensor catalog in the Southern California using SCEC 3D Community Velocity Models
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Motivation
A more accurate and comprehensive earthquake focal mechanism catalog is important to constraining the regional stress field, understanding tectonic processes, and potentially mitigating seismic hazards. Focal mechanisms of small-to-medium-size earthquakes in the Southern California region are routinely available through the Southern California Earthquake Center (SCEC) (Hutton et al., 2010; Yang et al., 2012). Usually, these focal mechanisms are determined by inverting either the P-wave first-motion polarities, S/P amplitude ratios, or seismic body and/or surface waveforms, and all of them assume simple 1D Earth velocity models (Zhu & Helmberger, 1996; Hardebeck & Shearer, 2002; Yang et al., 2012). However, recent tomographic studies demonstrate strong 3D velocity heterogeneities in the Southern California crust (Lee et al., 2014; Shaw et al., 2015), for example, the deep sedimentary basins and strong Moho lateral variations (Fig. 1). Thus, inversions based on simplified 1D velocity models may lead to biases and large uncertainties in focal mechanism solutions, as the complicated Earth 3D structure effects cannot be adequately quantified (Fig. 1).

To date, a series of 3D SCEC Community Velocity Models (CVMs) are available (Small et al., 2017), and these 3D velocity models have proved significantly more accurate in predicting the seismic waveforms compared to 1D velocity models (Lee et al., 2014). One of the main goals of these CVMs is to allow more accurate estimations of 3D Green’s functions, which can be used to improve source inversions. Thus, it is natural to consider using realistic 3D velocity models in source inversion, which shall allow us to improve waveform fits and inversion accuracy.

Methods
In the previous study, we developed a highly automated and efficient algorithm to determine the moment tensor for small-to-medium-sized earthquakes in the LA basin using 3D velocity models (Wang & Zhan, 2019). The previous results have shown that introducing a 3D velocity model could generally increase the accuracy of inverted moment tensors and produce better waveform fitting (Wang & Zhan, 2019). We now refine the workflow and extend the study area to entire Southern California. The new workflow contains two parts: Green’s function database building and the automated waveform inversion (Fig. 2). For the first part, we have calculated the Green’s function database for 296 broadband stations in the CI network. For each station, we extracted a local 3D velocity model (Lee et al., 2014) centered around it and then calculated the Green’s functions using the reciprocity-based 3D finite-difference modeling (Graves, 1996; Zhao et al., 2006; Zhu & Zhou, 2016). For the second part, the user will only need to define the event ID and the workflow will automatically calculate the earthquake’s full moment tensor by minimizing the waveform misfits between observations and synthetics. We also developed an alternative xcap package based on MATLAB GPU computing and python, which enables fast manual tuning and visualization when needed. More details about our algorithm are described in our previous publication (Wang & Zhan, 2019). The
current workflow is highly automatic. It can easily incorporate more stations in Southern California and continuously produce moment tensor catalog for future earthquake events with little human interference.

Figure 1. Seismicity and velocity structure in the study region. (a) Purple dots are seismicity from 1981 to 2018 with magnitude above 2.0 from Hauksson et al. (2012). The triangles are the permanent broadband seismic stations in this area, a large portion of which are located within or near the Los Angeles basin. (b) The latest version of the Southern California Earthquake Center (SCEC) Community Velocity Model (CVM)–CVM-S4.26 (Lee et al., 2014)–along the profile in (a). The standard 1D Southern California velocity model (SoCal) (Hadley & Kanamori, 1977) (red) and the 1D velocity models (black) extracted from the 3D CVM-S4.26 model (Lee et al., 2014) are compared to demonstrate the strong lateral heterogeneities in this area. (c) Waveform comparison among real data, the synthetics generated using the 1D SoCal and the 3D velocity models, indicating the strong 3D structure effects. The location of earthquake and locations of stations are given in orange star and triangles in (a).
Figure 2. Workflow for waveform-based moment tensor catalog using 3D Green’s functions. The workflow contains two parts: (i) Calculating the strain green tensor database using 3D finite-difference modeling with 3D SCEC CVM model. (ii) Cut-and-paste (CAP) 3D moment tensor inversion. The workflow is currently semi-automatic, which only requires the input of the event ID from the user. We also developed an alternative independent xcap moment tensor inversion package which enables fast manual tuning when needed.

Results

We applied our automated inversion procedure to 1530 earthquakes that have a local magnitude larger than 3.5 in Southern California using 296 stations in the CI network (Fig. 2). The total storage of the Green’s function database for 296 stations is about 14TB. For each earthquake, the workflow queries available stations within a 90 km-radius circle and retrieve the corresponding Green’s functions from the database. Our algorithm then automatically searches for the optimal focal mechanism that simultaneously minimizes the synthetic-observed misfit and maximizes the number of components that have correlation coefficients higher than 65%. We compared the focal mechanism of our new catalog (we call it CAP) with the YHS and SCSN moment tensor catalog (SCMT) in Fig. 4 under two different quality control criteria. For both criteria, our catalog is more consistent with the SCMT catalog, since the kagan angles between our catalog and SCMT catalog are systematically closer to zero (Kagan, 2007). In addition, we also inverted the non-double-couple components which show a systematically positive isotropic components for moderate earthquakes in entire Southern California (Cheng et al., 2021).

We show 66 inverted focal mechanism solutions from the 2019 Ridgecrest earthquake sequence in Fig. 6 as an example to compare the focal mechanism among CAP, YHS (Yang et al., 2012), and SCMT catalog. The solutions from our inversion procedure are mostly consistent with the YHS catalog and the SCMT (if they exist). For those inversion results that have great discrepancy among different catalogs, our inversion
results provide a more reasonable result in the sense of local stress direction and waveform fitting. As an example, we show one inversion report for event ID 38458079 on July 6\textsuperscript{th}, 2019 in Fig. 7. For this event, the HASH method produces a quality D focal mechanism while our method produces a very stable bootstrap result and good waveform fittings across 16 stations.

![Map of Southern California with earthquake data](image)

*Figure 3. Map for selected 296 stations (gray triangles) and more than 2000 small-to-medium-sized earthquakes (magenta dots) from 1980 to 2020 in Southern California in our study from Hauksson et al. (2012). The colored surface represents the number of stations available within 90 km for each point within the CVMS4.26 (Lee et al., 2014) model range. The two white contour lines represent the boundary for at least one station available (outside line) or five stations available (inside line).*
Figure 4. Comparison between our catalog (CAP), YHS catalog, and SCMT catalog. a) 362 common events among CAP, YHS, and SCMT catalog under the criteria that at least 20 waveform components were used in the CAP inversion. b) 250 common events among CAP, YHS, and SCMT catalog with extra criteria that the average cross-correlation coefficient between synthetic and observed waveforms are greater or equal to 80% and average variance reduction greater than 60%.

Figure 5. Lune plot of the inverted non-double-couple components. Color represents the density of events. Brighter color in the center means majority of the events are close to the pure double-couple solution. a) 750 out of 1530 earthquakes under the criteria that at least 20 waveform components were used in the CAP inversion. b) 507 out of 1530 earthquakes with extra
criteria that the average cross-correlation coefficient between synthetic and observed waveforms are greater or equal to 80\% and average variance reduction greater than 60\%. The inverted isotropic components show systematic positive pattern under both criteria.

Figure 6. Comparison of 66 example focal mechanisms from the 2019 Ridgecrest earthquake sequence between our solution (red), the YHS solution (black), and the SCMT solution (blue). These three different solutions are mostly consistent.
Figure 7. Focal mechanism inversion report for event ID 38458079 on July 6th, 2019. The red beach ball shows our inverted focal mechanism in comparison with the HASH method (the gray beach ball). We show the bootstrap histograms for 6 moment tensor components and the corresponding nodal lines (gray lines) on the beach ball. The location of the event and the stations used in the inversion are shown on the map. We also do a depth search for the optimal focal mechanism. The right panel shows the waveform fitting for this event.

In this study, we refined the workflow and expanded our study for small-to-medium-sized earthquakes from the LA basin (Wang & Zhan, 2019) to entire Southern California. We produced a Green’s function database for 296 stations in the CI network. We generated a new moment tensor catalog in Southern California with the completeness of ML ≥3.5. The new catalog is more consistent with the SCMT catalog than the YHS catalog. By comparing our catalog with the current catalogs, our results show that incorporating 3D velocity models can refine the existing moment tensor catalogs, resulting in more accurate focal mechanisms, focal depths, and moment magnitudes.
Reference


