Fault surface rupture in the 2023 Türkiye earthquakes from satellite and field data

Nadine G. Reitman, Madeleine Tan, Paula Burgi, Alex Hatem, Chris DuRoss, H. Ben Mason
U.S. Geological Survey, Geologic Hazards Science Center, Golden, Colorado, USA
nreitman@usgs.gov

Surface displacement measurements of large continental ruptures are critical constraints for unravelling earthquake behavior, deformation processes, and rupture at depth and constraining probabilistic fault displacement hazard models. Displacement happens over a range of scales – from localized, on-fault displacement over a few meters to displacement distributed up to ~1 km from the primary fault trace. Defining "true", or most representative, displacement values and uncertainty is a challenge because most methods of measuring offset are best suited to capture displacement at either narrow (e.g., field measurements, mapping on high-resolution images) or wide (interferometric synthetic aperture radar, pixel correlation) apertures, but not both. Furthermore, fault scarps, displaced features, and ground cracking are perishable data that may be erased by natural or anthropogenic causes (e.g., precipitation, rebuilding) soon after an earthquake. Therefore, rapid collection of surface rupture and displacement data from remote and on-the-ground sources is critical following large continental earthquakes. In this study we pose three primary questions: (1) What characteristics of surface rupture does each dataset best capture? (2) How can datasets be combined to quantify the "true" displacement? (3) With limited resources, where is it best to focus efforts during the rapid earthquake response phase?

The 6 February 2023 earthquakes in southern Türkiye provide an opportunity to compare the surface displacement results that can be generated from different datasets. The M7.8 Pazarcık and M7.5 Elbistan earthquakes occurred on the East Anatolian and Çardak faults, respectively, causing >500 km of combined surface rupture, >60,000 casualties, and affected >15 million people. Following the earthquakes, multiple teams measured offset features in the field, mapped surface rupture on high-resolution satellite images, and produced pixel correlation from radar and optical images of various resolutions. Here, we present slip distributions for both ruptures from pixel correlation of Planet optical images (3 m/pixel), which we compare to published slip distributions derived from pixel correlation of Sentinel-1 range and azimuth (30 m/pixel) and to slip distributions measured in the field. For a 30-km-long section of the East Anatolian fault, we also present pixel correlation of optical Sentinel-2 images (10 m/pixel) and displacement measurements from high-resolution (<1 m/pixel) WorldView images taken after the earthquakes. For the section with both field observations and high-resolution optical imagery, we present detailed comparisons of surface rupture width and displacement at individual sites with localized and distributed rupture measured in the field, remotely from high-resolution optical images, and from pixel correlation of medium- and low-resolution optical images.

The full-rupture analysis and detailed site investigations provide complementary but unique results. For both ruptures, the slip distributions from Planet, Sentinel-1, and field measurements record similar patterns but different amounts of displacement along the ruptures. Although all three datasets overlap within uncertainty in places, on average the field offset measurements are smaller than the Planet pixel correlation displacements, and the Planet pixel correlation measurements are slightly smaller than the Sentinel-1 pixel correlation displacements. For the M7.8 rupture on the East Anatolian fault, the field offset measurements are 31% and 39% smaller than the Planet and Sentinel-1 pixel correlation displacements, respectively, and the Planet displacements average 15% smaller than the Sentinel-1 displacements. For individual sites, we find that all datasets agree within uncertainty on displacement when the surface rupture is localized and displacement is large (~ 6.5 m). However, small displacements (~ 0.5 m) are below the detection resolution of the remote measurement methods and thus require fieldwork to accurately record. At a site with distributed displacement, the datasets agree within uncertainty on the displacement, but they resolve different numbers of fault strands. Deformation zone width is systematically larger by 1-2 orders of magnitude when measured with Planet pixel correlation than when mapped in the field or on high-resolution images.

From these comparisons, we find that all methods of measuring surface displacement are useful to characterize deformation in large continental earthquakes, but none alone capture the entire surface deformation field. When displacement is distributed, high-resolution remote datasets may better capture total deformation than on-the-ground methods, but low-resolution remote datasets do not capture the level of detail necessary to resolve individual fault strands. Conversely, when displacement is highly localized, field and high-resolution remote datasets accurately capture both displacement and rupture width, and low-resolution remote methods overestimate rupture width. For small displacement, on-the-ground response cannot be replaced by the remote methods used here. Which method is best may thus depend on the goals of the investigation. If the aim is to capture the full displacement field, including both elastic on-fault and diffuse inelastic deformation, pixel correlation may be better suited than field methods. However, if the goal is to capture discrete surface breaks to, for example, better parameterize off fault displacement models, then on-the-ground and high-resolution remote methods are necessary. We advocate for joint efforts to combine field-based and remotely sensed datasets in responding to large continental ruptures because no method alone captures the entire surface deformation field.