

Ground Truth of Surface Rupture and Near-Fault Strong Motion: Video, Seismic and Field

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Ground Truth of Surface Rupture and Near-Fault Strong Motion from Video, Seismic and Field

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Abstract

Seismic radiation and dynamic faulting have rarely been observed concurrently, limiting observational constraints on earthquake rupture processes and seismic hazards. Here we report the first directly validated observation of surface rupture and strong-motion generation captured by a security camera and corroborated by nearby seismic records and field measurements during the 2026 Kumamoto, Japan, earthquake. The near-fault ground motion comprised two velocity pulses generated by subsurface and surface fault ruptures, respectively.

Observing dynamic fault motion and strong-ground-motion generation is essential for understanding earthquake rupture processes^{1,2} and improving resilience to seismic hazards^{3,4}. Significant efforts have been devoted to capturing these phenomena at close range and high resolution⁵⁻⁸. Although satellite geodesy, particularly Synthetic Aperture Radar (SAR), has dramatically improved observations of coseismic fault deformation^{1,9}, direct observations linking dynamic fault slip to the generation of strong ground motion remain extremely rare. Recently, fault slip was captured for the first time by security camera footage identified from social media during the predominantly strike-slip 2025 Myanmar earthquake¹⁰. However,

nearby seismic records and contemporaneous field observations were unavailable, preventing cross-validation of the inferred fault motion and a direct evaluation of its relationship to strong-motion generation, surface deformation and damage.

Here we report the first directly validated observation of surface rupture and near-fault strong-motion generation using security-camera footage recovered through post-earthquake field investigations following the 2026 July 28 (Japan Standard Time) Kumamoto earthquake. This fatal Mj 7.1 (Mw 6.8)⁸ event ruptured the Hinagu Fault Zone in southwest Japan (Fig. 1a), producing surface faulting and widespread structural damage (Fig. 1b). The trans-tensional surface ruptures were observed in the field and by SAR along the previously mapped fault traces¹¹. The camera was located immediately adjacent to the rupturing fault and was complemented by nearby strong-motion stations and detailed field surveys conducted shortly after the earthquake. Synchronous visual and seismic observations, along with geological measurements, provide a uniquely verifiable record of fault motion and seismic radiation and offer the first opportunity to directly link subsurface rupture propagation, surface-break formation and near-fault strong-motion generation.

On August 2nd and 3rd, an author field-surveyed along the fault trace to collect footage from security cameras and driving recorders that may have captured fault slip. Cameras installed near the fault were mostly unrecorded due to the coseismic blackout, except at one site (Fig. 1a), where a local resident provided camera footage (before it was automatically overwritten a few days later). This study is based on original raw footage recovered through these post-earthquake field investigations and obtained directly from the recording system.

Fig. 1c shows the velocity and displacement waveforms recorded by K-NET¹² (KMM012 and KMM013), JMA (41509) and the local-government seismic-intensity network (93025-93057)¹³, capturing near-fault motion. Each waveform clearly shows the prominent velocity pulse

associated with the passage of the rupture front, as generally reproduced in dynamic rupture modelling^{1,14}. The permanent displacements consistently exhibited combined right-lateral and normal-fault slip (Fig. 1c). The recorded permanent displacement near the camera was consistent with that measured at a nearby GNSS station 940093 (north-eastward 87 cm and downward 33 cm).

To estimate near-fault strong-motion, we applied image correlation¹⁰ to retrieve displacement from security-camera images covering the on- and off-fault area (Fig. 1d and Methods). We used the captured motion of a car parked right next to the fault trace, headed nearly normal to the fault strike (Fig. 1e, Extended Data Fig. 1 and Supplementary Video 1), that moved significantly without a driver during the ground shaking. This large motion likely reflects loose braking on nearly level ground. The car, close to the camera, provides sufficient spatial resolution, along with high temporal sampling at 16 frames per second. This ~800 kg vehicle behaves as an inertial reference mass, allowing relative motion between the car and the ground to be used as a proxy for ground displacement (Method). We tracked the car's motion in pixel coordinates (Extended Data Fig. 2) and converted it to metric scale, calibrated using the actual distance between the markers (Method).

We identified the P-wave arrival at this site at 19 s after 16:27 (JST) by image correlation and recorded sound noise. Fig. 1f shows the retrieved displacement and velocity time series. They exhibit a two-step displacement pattern and a two-peak velocity pattern. These characteristics are not artefacts of observation or analysis, and are obviously captured in Supplementary Video 1. The individual velocity pulses have similar durations of ~1.5 s, and the maximum amplitude is ~1 m/s. The total duration of the displacement steps is ~4.5 s, with an amplitude exceeding 1 m. These amplitude estimates are comparable to the near-fault seismograms (Fig. 1c).

These image-retrieved time series closely match the nearby displacement seismograms in the

fault-normal components at stations 93055 and KMM012, located 3.7 and 4.8 km from the
 camera, respectively. The displacement wave began with a positive peak (due to the near-field
 term, as in seismology¹⁵) and then increased more significantly in the negative sense with the
 following S-wave toward the permanent displacement, with or without major oscillation
 afterwards, respectively, for the seismograms and the car motion. This sensitivity of the car
 motion to the weaker near-field term supports the reproducibility of the ground displacement,
 along with the similarity of the waveforms. The oscillatory component of the displacement
 seismograms resembles the velocity pattern of the car motion, with some time shift. The near-
 fault velocity and far-field displacement might be similar because of the proportionality
 involving retardation between the fault slip velocity D and the far-field displacement
 waveform¹⁵, u_{far} , as $u_{far}(r, t) \propto (1/r)D(t - r/V_s)$ with the source-receiver distance r , time
 t and S-wave speed V_s . While we need more rigorous validation, the two-peak pattern of the
 near-fault motion could have shaped the strong-motion away from the fault.

Next, we explore fault-displacement (slip) motion due to surface break and rupture
 propagation in the image data. Fig. 2a shows the analysed image covering the cultivated area,
 which hosts the fault. The fault is visible in the vegetated area after the earthquake (see
 Extended Data Fig. 3 and supplementary Video 2 for details). Displacement markers are placed
 on the walls of the buildings behind the green area to bracket the fault trace. Fig. 2b shows
 ortho-mosaic images of the 3D topographic model taken along the footpath (Fig. 1c) after the
 earthquake; we conducted the field measurements using lidar sensing and photogrammetry with
 an iPhone and Pix4D software. We estimate fault displacements of ~ 0.8 m along strike and ~ 0.9
 m vertically. We convert the fault motion in the 2D camera image to obtain the fault-parallel and
 vertical displacement components (Fig. 2c), neglecting the fault-normal component because it is
 difficult to quantify from the 2D image (Methods and Extended Data Fig. 4).

In Fig. 2c, we find that the fault slip starts at ~24 s, ~5 s after the P-wave arrival, and lasts ~2 s, though more precise determination is challenging given the relatively high noise level. Using the calibrated distance scale, we estimate the slip amounts at ~1.5 m horizontally and ~0.9 m vertically. The amount of the vertical displacement is comparable to that measured on the ground, while the horizontal component is slightly larger, probably because the lateral motion contains the contribution from the fault-normal motion (see Supplementary Discussion and Fig. S1). Given a net slip of ~1.5 m from the post-seismic ground survey, divided by ~2 s, we obtain the slip speed during the surface break to be ~0.75 m/s. This slip speed is on the same order as that estimated for the 2025 Manderley, Myanmar earthquake ¹⁰.

Further, we had a rare opportunity to directly compare observed time series of fault slip with off-fault displacement to understand the origin of the two-step pattern (Fig. 2d). We found that the fault did not move at the surface until ~24 s when the first (negative) rise occurred. In fact, fault slip occurred after the off-fault displacement settled once. These observations demonstrate that subsurface rupture generated the first displacement step (velocity pulse), whereas surface fault rupture generated the second. Such a comparison has not previously been possible because independent observational constraints on off-fault ground motion and on-fault slip have rarely been captured simultaneously within the same field of view.

The security camera footage provided further opportunity to analyse the along-strike propagation of the surface break (Fig. 2e and Extended Data Fig. 5). The observed rupture propagated from the middle of the cultivated area and propagated toward the northeast, opposite to the overall horizontal propagation (Fig. 1a). This apparent backward propagation suggests that the rupture propagated mainly upward in this area (illustrated in Fig. 2f). This observation allows us to propose a possible simple scenario that gives rise to the two velocity pulses.

The upward propagation pattern may reflect wave diffraction within the shallow sedimentary

structure overlying the seismological basement ($V_s \sim 3$ km/s) below ~ 500 m depth found in this area^{16,17}. As schematically illustrated in Fig. 2f, fault slip within the sedimentary layer likely involved a smaller stress drop¹⁸, and rupture exhibits lower seismic radiation than that in the basement rock¹⁹. Therefore, the higher seismic radiation from the basement rupture produced the first velocity pulse on the ground (Fig. 2f top), and it could decrease as the rupture extended into the sediments, lowering the ground velocity (Fig. 2f middle). As it propagated further toward the surface, ground velocity increased again since the elevated rupture-front velocity approached the surface, creating the surface-break pulse as the second peak velocity of the seismogram (Fig. 2f bottom).

Methods

Car Motion Analysis

To obtain the ground displacement time series, we analyse the relative motion between the ground and the car, which can be assumed to be an inertial reference mass (a fixed point). We neglect the effect of the car brake when estimating displacement from car motion. Although the brake was fully applied, the force of the parking brake could have had a small effect, considering the near-fault acceleration recorded of 1160 gal at station 93025. Japanese regulations require a parking brake to support a car's weight on a 20% slope²¹, i.e., ~20% of the gravitational acceleration, 980 gal. The inertia force during the current strong motion easily overcomes the braking force.

For the image correlation analysis, Markers 1 and 2 are placed on the car and on the white line on the ground, respectively (Fig. 1e). Tracking is performed in Python using OpenCV's MIL tracker (cv2.TrackerMIL); each marker is manually initialised with a bounding box in the first frame, and its position in subsequent frames is defined as the centroid of the tracked bounding box. The tracking result is shown in Extended Data Fig. 2a. To obtain ground displacement with camera shaking removed, we compute the motion of Marker 2 relative to Marker 1 by subtracting their positions (Extended Data Fig. 2b); this subtraction removes the common noise from the shaking. Pixel coordinates are converted to metric distances based on the field-measured length of the white line printed on the parking slot (4 m), which corresponds to approximately 386 pixels in the image; the field measurement is based on the satellite photograph in Google Earth (<https://earth.google.com>).

Frame numbers are likewise converted to seconds using the timestamp displayed in the camera image and the frame rate of 16fps. We confirm that the camera clock was synchronised

with a Network Time Protocol Server at a few-minute intervals. This provides enough clock-time accuracy for the current purpose. The ground displacement along the direction of car motion, shown in Fig. 1f, was then obtained as the signed distance from the origin (0, 0), where the sign is determined by the x-coordinate, with the southeast direction defined as positive (see map view in Fig. 1d).

Fault Slip Analysis

To obtain the time series of the fault slip, we analyse the relative motion of two markers placed across the fault line (cyan and blue; see Fig. 2a). The cyan marker is placed on the leftmost window of the building behind the cultivated area, and the blue marker is placed on a white-coloured object nearby across the fault trace. Because the image resolution near the fault is too low for reliable automatic tracking, the markers are manually tracked in every frame during the fault slip (71 frames), plus one frame each before and after the shaking, to obtain the markers' initial positions and the final displacement estimate.

The tracking result is shown in Extended Data Fig. 4a, and the tracking data were converted from pixel scale to metric scale. The metric scales of the markers in the 2D image (Fig. 2a) are measured on the 3D model obtained in the field (Fig. 2b). The horizontal scaling factor in the image is calculated from the scale bar (see Fig. 2a) and the angle between the scale bar direction and the camera's line of sight. Extended Data Fig. 4b shows a schematic map view, in which a horizontal scale bar of known length L [m] corresponds to N_L pixels along the image's x -axis. The horizontal scaling factor is then given by $L \sin \theta / N_L$ [m/pixel], where θ is the angle between the camera's line-of-sight direction and the scale bar; here $\theta = 34^\circ$, as measured from the satellite photograph. The vertical scaling factor is obtained simply by dividing a known real-world vertical distance by the corresponding pixel number. However, no

vertical reference of known length was available near the blue marker, so we could not measure its vertical scaling directly. Instead, we calculated the blue marker's vertical scaling from the cyan marker's vertical scaling, scaled by the ratio of the blue-to-cyan horizontal scaling factors, assuming the vertical-to-horizontal scaling ratio is the same for both markers. The resulting scale factors [m/pixel] are: 0.095 (cyan, vertical), 0.063 (cyan, horizontal), 0.126 (blue, vertical), and 0.084 (blue, horizontal). We thus obtained the metric-scale, image-projected displacement of each marker, shown in Extended Data Fig. 4c.

Taking the difference between the two markers' displacements yields the fault slip as projected onto the camera's x -direction (U in Extended Data Fig. 4d), which is shown in the map view in Extended Data Fig. 4b. As illustrated in Extended Data Fig. 4b, U is related to the true right-lateral slip u by $U = u \cos \phi$, where ϕ is the strike of the fault ($\sim N60^\circ E$, referring to our field measurement); the upward slip requires no such conversion. The converted right-lateral and upward slip is shown in Fig. 2c and Extended Data Fig. 4e (in a different axis set), with the final fault slip calculated in the same way from frames before and after the shaking, estimated as 1.5m right-lateral and 0.9m upward.

Four assumptions underlie the conversion described above: (1) the camera points directly toward the area under consideration, as indicated by the fault being centred along the horizontal axis of the camera image; (2) the distance between the markers and the fault (~ 80 m) is sufficiently larger than the lengths of the scale bars (3.4 m and 6.0 m), the vertical extent of the region considered (~ 5 m), and the fault slip (~ 1 m), so that θ can be treated as approximately constant and the scaling can be treated within the two-dimensional plane shown in Extended Data Fig. 4b; (3) the slip is purely right-lateral and upward; (4) the fault line in the image is tilted by approximately 4° from horizontal, but this tilt is sufficiently small and is therefore neglected in the conversion.

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Author contribution

RA led the project and obtained security camera footage and analysed the seismograms. MM analysed the image data. All authors contributed to the paper writing.

Competing interests

The authors declare no competing interests.

Data availability

The data supporting the findings of this study are available within the article and its Supplementary Information.

Code availability

The OpenCV library is provided under Apache License 2.0 and is available at <https://github.com/opencv/opencv>. We used strong-motion records provided by the Japan Meteorological Agency (JMA), Kumamoto Prefecture and the National Institute for Disaster Resilience (NIED).

Figures and legends

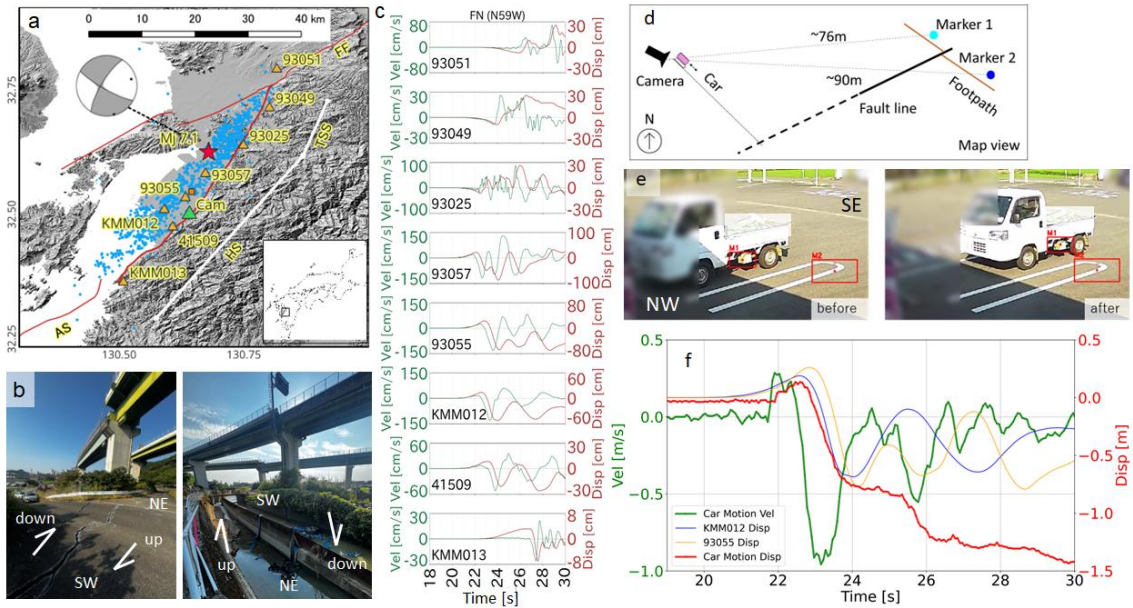


Fig. 1. The 2026 Kumamoto earthquake and near-fault observations. (a) Simplified active fault traces (red lines), for the Hinagu Fault zone including TSS Takano-Shiharata Segment, which hosted the 2016 Mw 6.2 foreshock²⁰, HS Hinagu Segment) and AS (Ariakekai Segment) and FT (Futagawa fault, which hosted the 2016 Mw 7.0 mainshock²⁰). The mainshock hypocentre (yellow star) and centroid moment tensor (beach ball) are shown together with aftershocks occurring within one day of the mainshock (cyan dots). The green triangle indicates the camera location. Yellow triangles and an orange square indicate seismic and GNSS stations. The shaded relief is based on topography from GSI Maps. (b) Opposite views of offset bridges and surface ruptures at a site near the camera location. (c) Fault normal component velocity (green) and displacement (red) seismograms recorded at the stations shown in (a). Signals were low-pass filtered at 0.1 seconds. South-eastward motions are positive. Possible instrumental drifts at later times are not corrected. (d) Camera configuration showing the fault and the parked car. Markers were used for the image-correlation analysis shown in Fig. 2a. The footpath was used for field measurements of fault displacement, shown in Fig. 2b. (e) Analysed images

before and after the car motion (see Extended Data Fig. 1 and Supplementary Video 1 for the full temporal evolution). Red rectangles indicate markers used for image correlation. The vegetated area behind the car hosts the fault. Portions of the images have been altered to protect personal information and privacy. (f) Displacement (red) and velocity (green) waveforms derived from the car motion, together with displacement seismograms from stations KMM012 (blue) and 93055 (orange).

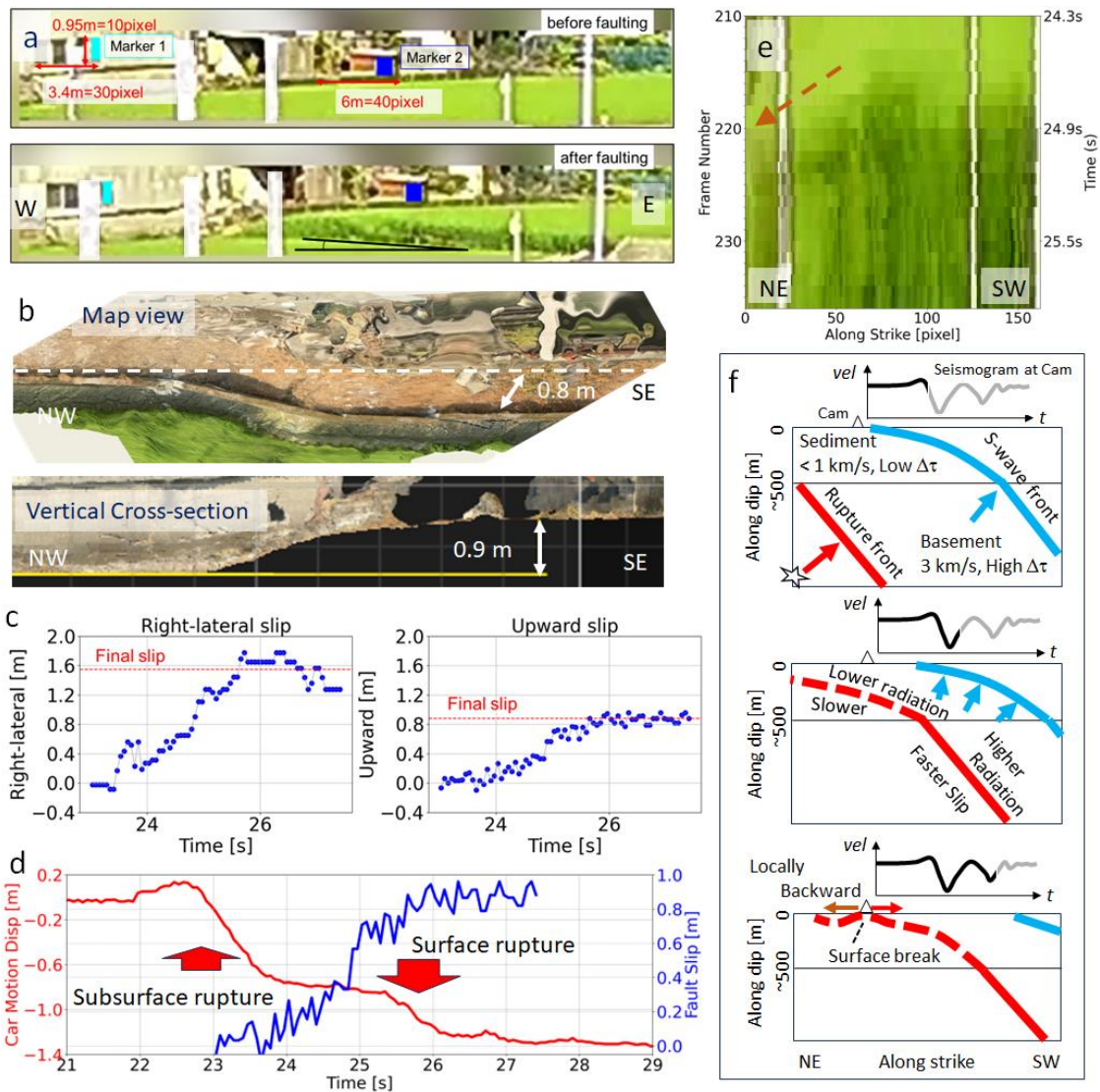


Fig. 2. Direct observation of fault displacement and surface rupture. (a) Images showing the analysed fault motion within the cultivated area (see Extended Data Fig. 3 and Supplementary Video 2 for the temporal evolution). Blue and cyan rectangular markers bracket the fault trace. Portions of the images have been altered to protect personal information and privacy. (b) Orthomosaic images of the 3D model surveyed along the footpath behind the cultivated area. Fault-parallel and vertical displacements across the fault are indicated. (c) Retrieved fault-parallel (right-lateral positive) and vertical (normal-faulting positive) components of fault displacement. (d) Comparison of off-fault displacement and velocity time series with fault

displacement. The second stage of the two-step off-fault motion coincides with surface fault slip. (e) Temporal and along-strike evolution of fault slip. Darker green areas indicate portions of the fault undergoing displacement (see Supplementary Fig. S3 for details of the analysis). The rupture emerged in the middle of the cultivated area and propagated mainly toward the northeast, opposite to the overall rupture-propagation direction. (f) Schematic illustration of a possible mechanism for the apparent backward rupture propagation and the two negative velocity pulses. The evolution of the rupture front and S-wave front is indicated by red and cyan lines, respectively. The dotted red line denotes rupture propagating through the sedimentary layer, where lower S-wave velocity and smaller stress drop, $\Delta\tau$, may reduce seismic radiation. Representative velocity seismograms at each stage are illustrated.

Supplementary Files

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