

A Method for Consistent Decomposition of Regional Near-Fault Ground Motions into Dynamic and Fault-Slip-Induced Components

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ABSTRACT

Reliable separation of dynamic and fault-slip-induced components in near-fault ground motions remains a critical challenge for regional seismic analysis because existing approaches have been primarily developed for individual records and lack spatial consistency. This study proposes a unified frequency-based framework in which a single optimal cutoff frequency is determined through a global objective function evaluated over all spatial locations. The results indicate that an optimal cutoff frequency of 0.29 Hz provides the best overall decomposition, corresponding to a mean objective function value of 0.208 and a standard deviation of 0.078, reflecting both good decomposition performance and limited spatial variability. The proposed framework enables consistent separation of acceleration-dominated dynamic motion and displacement-dominated fault-slip-induced deformation across the regional ground-motion field. Based on the decomposed components, spatial distributions of peak ground-motion parameters and response spectra are analyzed to quantify their respective contributions. The results show that dynamic components control acceleration-related responses, whereas fault-slip-induced components dominate permanent displacement and long-period spectral behavior. Directional spectral analysis further reveals a clear difference between the fault-parallel and fault-normal directions. In the fault-parallel direction, the fault-slip-induced component becomes dominant at long periods, leading to a pronounced transition from dynamic to fault-slip-controlled response. In contrast, in the fault-normal direction, the dynamic component remains significant even at long periods, and the contribution of the fault-slip-induced component is comparatively limited. These results indicate that the influence of fault slip on seismic response is strongly direction dependent, with a much greater impact in the fault-parallel direction than in the fault-normal direction. These findings demonstrate that a unified cutoff frequency can effectively ensure consistent decomposition across a regional ground-motion field while revealing the distinct and direction-dependent roles of dynamic motion and fault-slip-induced deformation in near-fault seismic response.

KEY POINTS

- Existing methods do not address consistent decomposition of near-fault ground motions across a region.
- A single cutoff frequency enables consistent separation of dynamic and fault-slip-induced components.
- The method supports consistent seismic input for structures near or crossing active faults.

INTRODUCTION

Near-fault earthquakes have been widely recognized for their strong destructive potential, particularly due to the complex ground-motion characteristics induced by fault rupture processes (Hall *et al.*, 1995; Somerville *et al.*, 1997; Chang, Wu,

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et al., 2025). Compared with far-field events, near-fault ground motions exhibit distinctive features such as rupture directivity and velocity pulses (Somerville, 2003; Bayless *et al.*, 2024; Withers *et al.*, 2024; Zhang *et al.*, 2024; Yen *et al.*, 2025), as well as permanent ground displacement and fling-step effects (Hisada and Bielak, 2003; Hisada and Tanaka, 2021; Yang *et al.*, 2024; Chang, Li, *et al.*, 2025). These characteristics can impose significant demands on engineering structures located in the vicinity of active faults, particularly those sensitive to displacement and long-period effects (Malhotra, 1999; Mavroeidis *et al.*, 2004; Kenawy and Pitarka, 2025; Luo, Li, *et al.*, 2026).

A fundamental characteristic of near-fault ground motion is that it consists of two physically distinct components: the dynamic component associated with seismic-wave propagation and the fault-slip-induced component related to permanent ground deformation caused by fault rupture (Hisada and Bielak, 2003; Dreger *et al.*, 2011; Hisada and Tanaka, 2021). These two components differ not only in their generation mechanisms but also in their effects on structural response (Dreger *et al.*, 2011; Jia *et al.*, 2024; Kenawy and Pitarka, 2025). The dynamic component primarily governs acceleration-related inertial effects (Luco and Sotiropoulos, 1985; Ghahari *et al.*, 2010; Zhao *et al.*, 2013), whereas the fault-slip-induced component contributes predominantly to displacement demands (Chen and Loh, 2007; Kamai *et al.*, 2014; Jia *et al.*, 2024; Geng *et al.*, 2025). For structures located near or crossing active faults, the coexistence of these two components poses significant challenges for seismic analysis, highlighting the necessity of distinguishing them in a physically meaningful manner (Boore *et al.*, 2002; Akkar and Boore, 2009; Yang *et al.*, 2024; Zhou *et al.*, 2024; Luo, Du, *et al.*, 2026).

Deterministic simulation methods have been extensively employed to reproduce near-fault ground motion by explicitly modeling rupture processes and wave propagation in heterogeneous media (Graves and Pitarka, 2016; Rodgers *et al.*, 2020; Artale Harris *et al.*, 2025; Shaw *et al.*, 2025). Such approaches are capable of capturing key physical features of near-fault earthquakes, including rupture directivity, fling-step effects, and spatially coherent ground deformation associated with fault slip (Hisada and Tanaka, 2021; Paolucci *et al.*, 2021; Pitarka *et al.*, 2021; Cao and Mavroeidis, 2024; Cao *et al.*, 2025). Consequently, deterministic simulations provide a physically consistent representation of both dynamic motion and fault-induced permanent deformation over a spatially distributed ground-motion field (Rodgers *et al.*, 2020; Paolucci *et al.*, 2021; Artale Harris *et al.*, 2025; Cao *et al.*, 2025). In contrast, stochastic and hybrid methods are primarily designed to reproduce the statistical characteristics of ground motion, particularly in the high-frequency range (Graves and Pitarka, 2010; Wu *et al.*, 2016; Paolucci *et al.*, 2018). Although hybrid approaches incorporate deterministic low-frequency components, the combination of independently generated signals may not fully preserve the physical consistency required to

represent fault-slip-induced deformation across a regional scale (Graves and Pitarka, 2010; Wu *et al.*, 2016; Paolucci *et al.*, 2018). Therefore, for studies focusing on the separation and characterization of dynamic and fault-slip-induced components within a regional ground-motion field, deterministic simulation provides a more appropriate framework.

Despite advances in near-fault ground-motion simulation and the increasing recognition of fault-slip effects on structural response, existing studies on component separation are predominantly conducted at the level of individual ground-motion records (Graves and Pitarka, 2010; Wu *et al.*, 2016; Paolucci *et al.*, 2018). In most cases, the cutoff frequency used to distinguish dynamic and fault-slip-induced components is selected empirically or optimized for a single record, without considering spatial consistency across a ground-motion field (Zhao *et al.*, 2016; Xin and Yang, 2020; Yang *et al.*, 2024; Chang, Li, *et al.*, 2025; Geng *et al.*, 2025). As a result, different locations may adopt different decomposition parameters, leading to inconsistencies in the separated components. This issue becomes particularly critical when spatially varying ground motions are used as input for structural analysis because inconsistent decomposition may affect the reliability of predicted structural responses. Therefore, there is a clear need for a unified decomposition framework that can determine an optimal and consistent cutoff frequency for regional ground-motion fields.

To address this issue, this study develops a method for consistent decomposition of near-fault ground motions across a regional domain into dynamic and fault-slip-induced components. A spatially distributed ground-motion field is first simulated for a near-fault site using deterministic simulation. Based on this dataset, a global objective function is established to determine the optimal cutoff frequency that ensures consistency of decomposition across all locations. The proposed approach enables a regionally consistent separation of the two components, providing a reliable basis for subsequent analysis. Furthermore, the spatial characteristics of the decomposed components are investigated in terms of peak ground-motion parameters and response spectra. The main contributions of this study are summarized as follows: (1) a regionally consistent decomposition framework based on an optimized cutoff frequency is proposed, (2) the spatial distributions and spectral characteristics of dynamic and fault-slip-induced components are systematically quantified, and (3) the transition of dominant mechanisms with respect to structural period and direction is identified and interpreted.

NUMERICAL SIMULATION OF GROUND MOTIONS AT THE CROSS-FAULT SITE

To investigate the coupled effects of seismic ground motion and fault slip in near-fault regions, a 3D numerical simulation of ground motions is conducted for a representative cross-fault engineering site in Jiaozhou Bay, China. The broadband ground motions are generated using the finite-difference code

SW4 in combination with a kinematic rupture model based on the Graves and Pitarka (GP) approach (Graves and Pitarka, 2010, 2015). A detailed 3D model incorporating realistic topography and heterogeneous velocity structures is established. The resulting large-scale ground-motion dataset, consisting of >240,000 time histories, provides a robust basis for the subsequent decomposition of seismic motion and fault-slip components.

Geological and engineering background

Jiaozhou Bay is located on the southeastern coast of the Shandong Peninsula, China, and serves as a key transportation hub connecting the eastern and western regions of Qingdao. Several major cross-sea infrastructures, including tunnels and bridges, have been constructed or are under development in this area (Qu, 2024). The region is intersected by the Cangkou fault, an active strike-slip fault that extends across the bay and directly intersects planned tunnel alignments (Luan *et al.*, 2010). The location of the study area, fault trace, and numerical simulation domain is illustrated in Figure 1.

According to geological investigations, the fault is characterized by a strike of $\sim 35^\circ$, a dip angle of 75° , and a rake angle of 180° (Jian *et al.*, 2017). The fault is relatively shallow, with a minimum burial depth of ~ 1 km and a seismogenic depth of ~ 5.5 km. The rupture length is estimated to be ~ 22 km, indicating significant seismic potential (Luan and Zhang, 2001). The complex tectonic setting and the presence of critical cross-fault infrastructures make this site a representative case for investigating the coupled effects of fault slip and seismic ground motion in near-fault regions.

Rupture source model

A kinematic rupture model based on the GP approach is adopted to simulate the earthquake source. The GP model generates spatially correlated heterogeneity in slip, rupture time, and slip-rate parameters and has been widely used for broadband ground-motion simulations because it can reproduce both low- and high-frequency characteristics of seismic waves (Graves and Pitarka, 2010, 2015; Luo *et al.*, 2024). In this study, the high-slip areas discussed subsequently are identified a posteriori from the generated rupture model, provided in standard rupture format (SRF), and are referred to as high-slip patches.

In this study, the earthquake magnitude is estimated as M_w 6.3 based on empirical relationships between rupture dimensions and seismic magnitude (Wells and Coppersmith, 1994). The fault rupture is modeled with a length of 22 km and a width of 9 km, consistent with geological observations. The hypocenter is located at the geometric center of the fault plane with a depth of 5.5 km. The spatial distributions of slip, rupture initiation time, and peak slip rate are generated using the broadband platform (BBP), providing a realistic representation of rupture propagation. The spatial distributions of slip, rupture initiation time, and peak slip rate are shown in

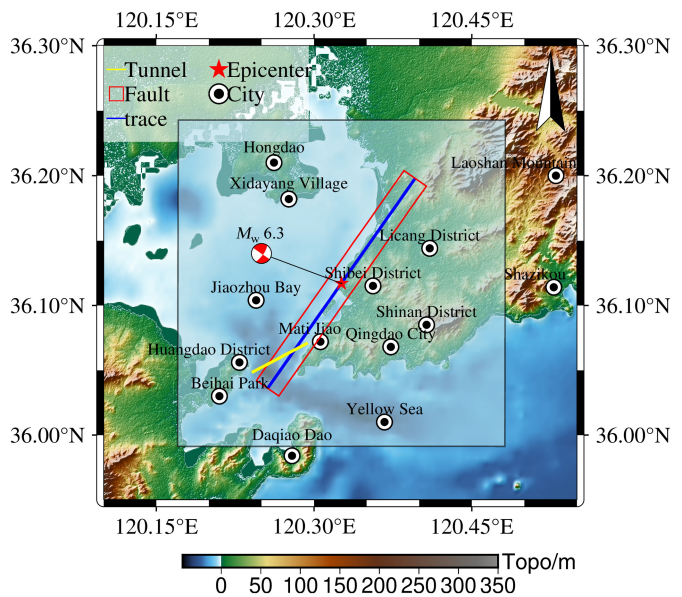


Figure 1. Location of the Jiaozhou Bay cross-fault engineering site and numerical simulation domain. The blue line denotes the surface fault trace, the red rectangle denotes the surface projection of the finite-fault plane used in the rupture simulation, and the gray rectangle denotes the SW4 computational domain. The red star indicates the epicenter, and the yellow line indicates the tunnel alignment. The color version of this figure is available only in the electronic edition.

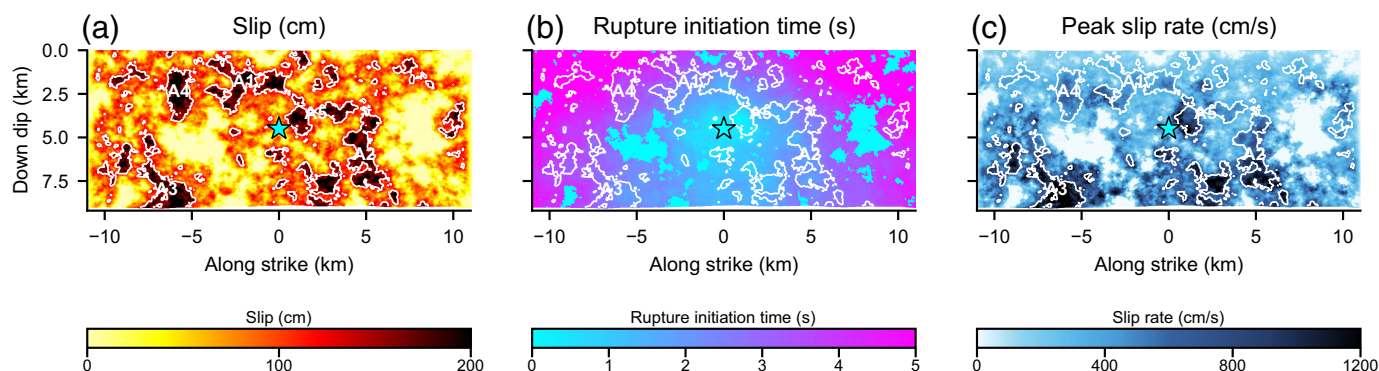
Figure 2, illustrating the heterogeneous rupture characteristics of the fault. The heterogeneity of rupture parameters plays a critical role in generating broadband ground motions.

To quantify the statistical characteristics of the generated rupture, we analyzed the SRF model on the fault plane. The SRF grid contains 550×225 subfaults with a spacing of $40 \text{ m} \times 40 \text{ m}$. Slip ranges from 0 to 2.90 m, with a mean of 0.81 m, median of 0.80 m, and standard deviation of 0.54 m. The coefficient of variation is 0.67. Rupture-initiation time ranges from 0 to 8.2 s, and the peak slip rate reaches 27.9 m/s.

High-slip patches were identified as contiguous areas with slip greater than or equal to the mean plus 1 standard deviation, that is, $\text{slip} \geq 1.35 \text{ m}$, and with area $\geq 0.50 \text{ km}^2$. This criterion gives 15 retained high-slip patches. Five major high-slip patches have areas $\geq 3.0 \text{ km}^2$, with centroids at approximately $(-2.0, 1.8)$, $(4.9, 6.0)$, $(-6.4, 8.0)$, $(-5.8, 2.4)$, and $(2.1, 3.6)$ km in the along-strike and down-dip coordinate system. The hypocenter is located at along-strike distance 0.0 km and down-dip distance 4.5 km, giving hypocenter-to-centroid distances of 3.3, 5.1, 7.3, 6.1, and 2.3 km for these five major high-slip patches. The moment fraction above the high-slip threshold is 0.35.

Three-dimensional topography and velocity structure model

The 3D velocity structure of the study area is constructed mainly from USTClitho2.0 (Han *et al.*, 2022), with density information supplemented by the global CRUST1.0 model



(Laske *et al.*, 2013). The velocity–density model was interpolated to the same horizontal sampling as the topographic grid used by SW4. In the input files, both the topography file and the material file follow the topographic grid, with a 30 m horizontal sampling interval. This value gives the sampling interval of the SW4 input grids after interpolation. The spatial distributions of *P*- and *S*-wave velocities at different depths are illustrated in Figure 3.

Topography was incorporated in SW4 through a gridded free-surface representation, and the 3D material model was provided as an external material-property file on the same horizontal sampling grid. At a representative grid point, the *S*-wave velocity of the shallowest model layer is 2926 m/s. The material properties were internally interpolated by SW4. Seawater was not explicitly modeled. The computational model was treated as an elastic solid medium with a topographic free surface. No additional site-specific low-velocity soil layer was introduced.

Numerical simulation setup and ground-motion dataset

A 3D finite-difference simulation is conducted using the SW4 code to simulate broadband ground motions for the study area. The computational domain is 28 km × 28 km × 16 km, with a uniform finite-difference grid spacing of 40 m and a 30-grid-point supergrid absorbing layer. No local mesh refinement was used. The 40 m spacing is a numerical discretization for wave propagation and should not be interpreted as the geological resolution of the underlying velocity model. The minimum *S*-wave velocity specified in the SW4 input is ~2.89 km/s, corresponding to ~7.2 grid points per shortest *S*-wave wavelength at 10 Hz, which falls within the 6–10 grid-point-per-wavelength range recommended in the SW4 user's guide (Petersson *et al.*, 2023).

The total simulation duration is set to 30 s to capture the complete ground-motion time histories, including both dynamic shaking and permanent displacement components associated with fault slip. Absorbing boundary conditions are applied at the model boundaries to minimize artificial wave reflections.

A dense array of virtual stations is distributed throughout the study area to record ground-motion time histories. In total, >240,000 ground-motion records are obtained, covering a wide

Figure 2. Fault rupture model used in the SW4 simulations. (a) Spatial distribution of slip, (b) rupture-initiation time, and (c) peak slip rate on the finite-fault plane. The color version of this figure is available only in the electronic edition.

spatial range across the fault zone. This large-scale dataset provides a robust and statistically representative basis for the subsequent decomposition of seismic motion and fault-slip components, enabling a systematic investigation of their spatial characteristics.

SW4 is used here to capture the model-resolved near-fault permanent-displacement field over the regional simulation domain, and the following decomposition is interpreted at this model-resolved spatial scale.

A UNIFIED FREQUENCY-BASED DECOMPOSITION FRAMEWORK FOR DYNAMIC AND FAULT-SLIP-INDUCED GROUND-MOTION COMPONENTS IN NEAR-FAULT REGIONS

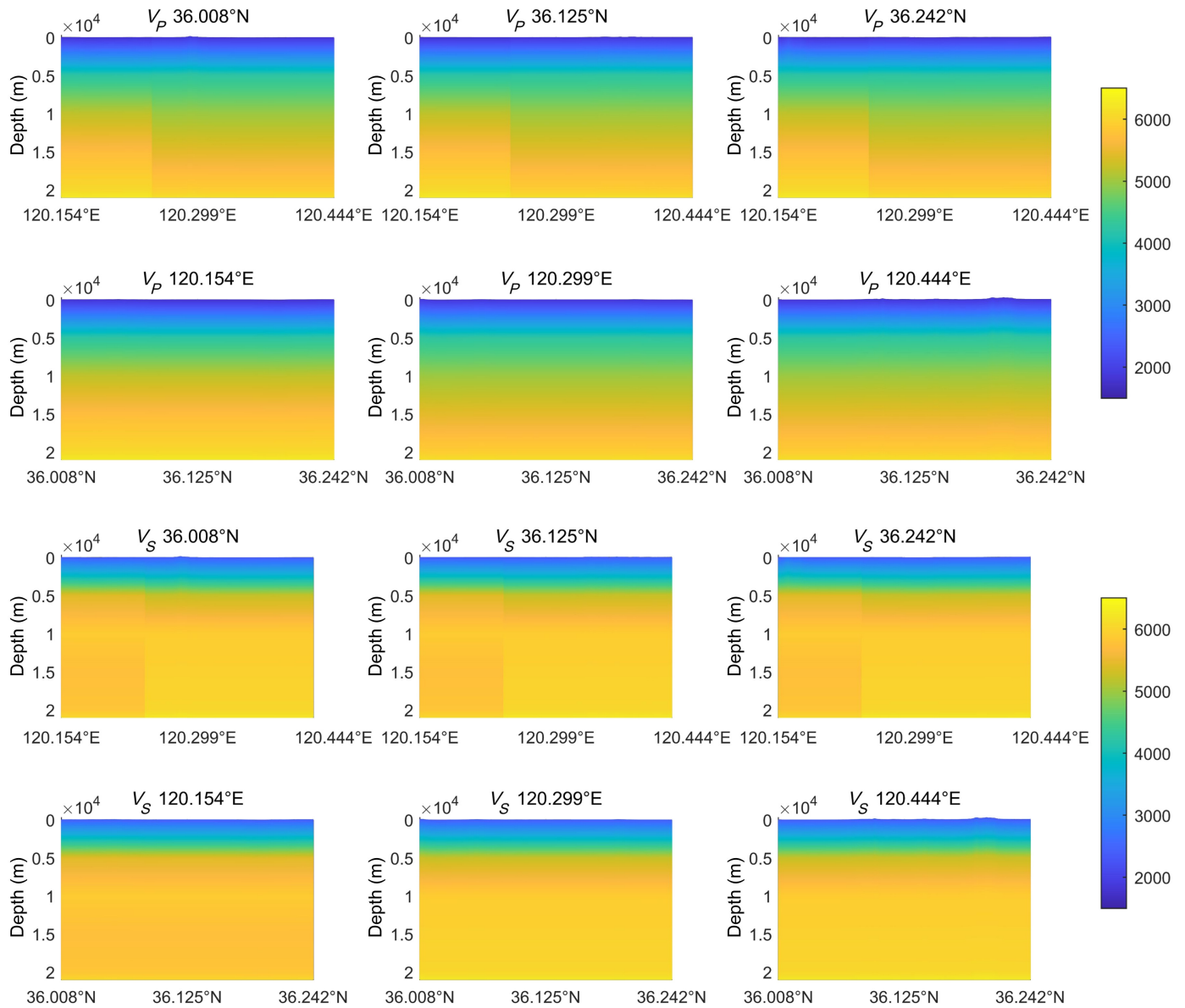
Physical characteristics of near-fault seismic motion and fault slip

Although frequency-domain filtering provides a practical approach to separate dynamic and fault-slip-induced components, the selection of the cutoff frequency remains a critical issue (Ghahari *et al.*, 2010; Yalcin and Dicleli, 2020). In near-fault regions, the characteristics of ground motions vary spatially, and using different frequencies for individual records may lead to inconsistencies in the decomposed components across a large-scale ground-motion field.

Therefore, instead of focusing on improving the decomposition accuracy for a single ground-motion record, this study aims to establish a unified and physically consistent criterion for determining the optimal separation frequency for a large set of ground motions. Such a framework ensures the consistency of decomposed components in subsequent structural response analyses under spatially varying seismic inputs.

Dual-objective optimization framework for component decomposition

To achieve a unified and physically consistent decomposition of dynamic and fault-slip-induced components across a large-



scale ground-motion dataset, a dual-objective optimization framework is proposed to determine the optimal separation frequency.

For a given cutoff frequency f_c , each ground-motion record is decomposed into a dynamic component and a fault-slip-induced component using sixth-order Butterworth filters with the 3 dB frequency set to f_c . The low-pass component is interpreted as the fault-slip-induced component, and the high-pass component is interpreted as the dynamic ground-motion component. Before this decomposition, the original acceleration records are low-pass filtered below 10 Hz using a sixth-order Butterworth filter. The displacement time histories used in the objective function are calculated from the filtered acceleration time histories using the Newmark integration method.

The final static offset of a simulated displacement time history provides an endpoint measure of the permanent displacement, but subtracting this single-endpoint value from the whole record does not describe the time evolution of the fault-slip-

Figure 3. P - and S -wave velocity slices along latitude and longitude in the study area. The color version of this figure is available only in the electronic edition.

induced component during rupture and wave propagation. Therefore, the present decomposition is applied to the full time history rather than only correcting the final displacement offset

$$J_i(f_c) = \alpha \left\| \frac{u_i^{\text{dynamic}}(t, f_c)}{u_i(t)} \right\|_2 + \beta \left\| \frac{\text{acc}_i^{\text{fs}}(t, f_c)}{\text{acc}_i(t)} \right\|_2, \quad (1)$$

in which $u_i(t)$ and $\text{acc}_i(t)$ denote the displacement and acceleration time histories of the original ground motion, respectively. Here, $u_i^{\text{dynamic}}(t, f_c)$ represents the displacement of the dynamic component, and $\text{acc}_i^{\text{fs}}(t, f_c)$ denotes the acceleration of the fault-slip-induced component. The operator $\| \cdot \|_2$ indicates the L2 norm over the entire time duration.

Based on the individual objective functions, the global objective function is defined as the mean value over all N ground-motion records:

$$\bar{J}(f_c) = \frac{1}{N} \sum_{i=1}^N J_i(f_c). \quad (2)$$

In addition, the standard deviation of the objective function is computed as

$$\sigma_J(f_c) = \sqrt{\frac{1}{N} \sum_{i=1}^N (J_i(f_c) - \bar{J}(f_c))^2}. \quad (3)$$

The first term in $J_i(f_c)$ ensures that the fault-slip-induced component preserves the displacement characteristics of the original ground motion, and the second term enforces that the dynamic component retains the acceleration characteristics. By minimizing the global objective function $\bar{J}(f_c)$, the proposed framework identifies a cutoff frequency that provides an optimal balance between displacement- and acceleration-related features across the entire dataset.

The weighting coefficients α and β control the relative importance of the two objectives. In this study, equal weights are adopted, with $\alpha = 0.5$ and $\beta = 0.5$, reflecting the comparable significance of displacement and acceleration in near-fault ground-motion analysis. No additional regularization term is introduced.

The cutoff-frequency optimization is implemented as a bounded discrete grid search. The allowable candidate range is $0.10 \leq f_c \leq 1.00$ Hz with an increment of 0.01 Hz. For each candidate value, the objective function is evaluated over all stations and three motion components, and the frequency corresponding to the minimum global objective function is selected as the optimal cutoff frequency.

Unlike conventional approaches that determine the cutoff frequency individually for each ground-motion record, the proposed framework evaluates the objective function over the entire dataset, enabling the determination of a single optimal separation frequency. This ensures the consistency of decomposed components in subsequent structural response analyses under spatially varying seismic inputs.

Determination of the optimal separation frequency

To achieve a unified decomposition of regional ground motion into dynamic and fault-slip-induced components, the objective function defined earlier is evaluated over candidate cutoff frequencies from 0.10 to 1.00 Hz with an increment of 0.01 Hz, giving 91 candidate values. For each candidate cutoff frequency f_c , the objective function is computed at all spatial locations and for all three motion components, and the global objective function is obtained over the full dataset.

Figure 4 shows the variation of $\bar{J}(f_c)$ and $\sigma_J(f_c)$ with respect to the cutoff frequency, together with the corresponding $\pm 1\sigma$ range. The mean value reflects the overall quality of the

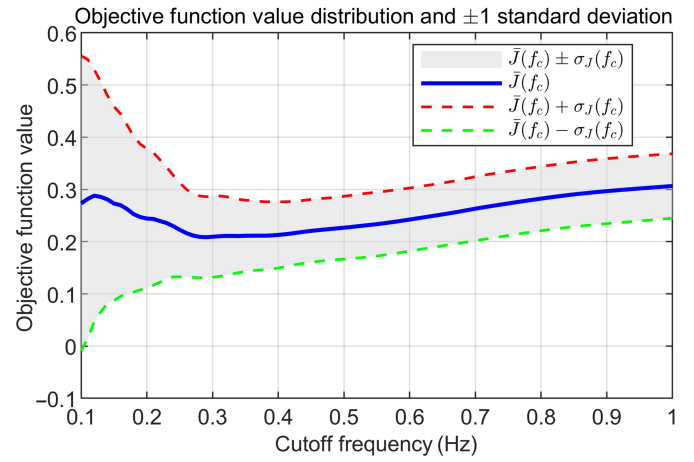


Figure 4. Variation of the objective function with cutoff frequency for the entire ground-motion dataset. The color version of this figure is available only in the electronic edition.

decomposition, and the standard deviation indicates the variability of the optimal decomposition behavior across different locations. A smaller standard deviation implies that a similar cutoff frequency is suitable for more locations, leading to a more consistent decomposition.

As shown in Figure 4, the mean objective function decreases initially and reaches a minimum at 0.29 Hz, with a value of 0.208. The corresponding standard deviation is 0.078. For lower cutoff frequencies, although the mean value remains relatively small, the standard deviation increases, indicating that the optimal decomposition varies more significantly across locations. For higher cutoff frequencies, the standard deviation decreases, but the mean objective function increases, suggesting a reduction in decomposition accuracy.

These results indicate that both the mean and standard deviation of the objective function should be considered. A suitable cutoff frequency should simultaneously yield a low mean value and a small standard deviation, ensuring both good decomposition performance and limited spatial variability. Therefore, a cutoff frequency of 0.29 Hz is adopted in this study because it provides the minimum mean objective function while maintaining a relatively low level of spatial variability. This choice allows a unified and physically consistent decomposition of dynamic and fault-slip-induced components across the regional ground-motion field.

We further evaluated the distance dependence of the global cutoff frequency by grouping stations into rupture-distance bins of 0–2, 2–5, 5–10, 10–15, and 15–20 km, as shown in Figure 5. The 5–10 km bin gives the same optimum as the full dataset (0.29 Hz). The 0–2 and 2–5 km bins give optima of 0.39 and 0.31 Hz, but using 0.29 Hz increases the objective function by only 0.7% and 0.9%, respectively. The farther 10–15 and 15–20 km bins show larger shifts, with optima of 0.45 and 0.39 Hz and objective-function increases of 4.8% and 7.0%

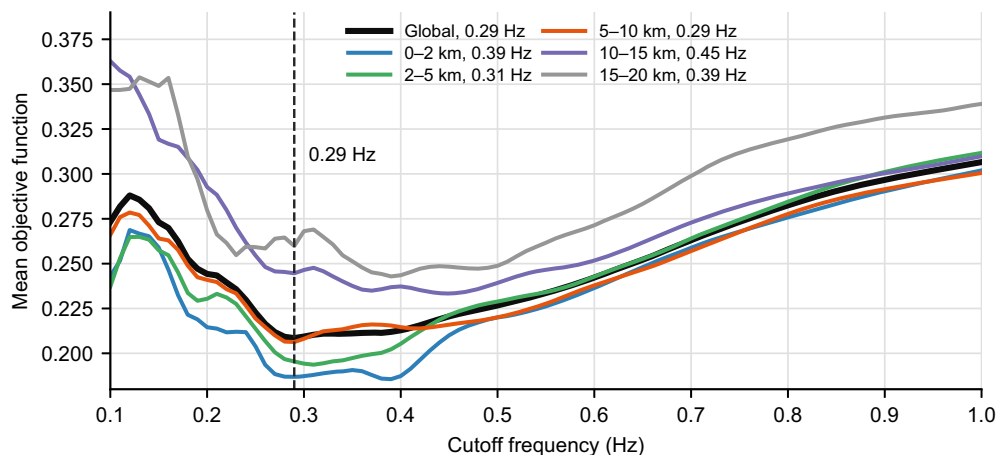


Figure 5. Distance-dependent sensitivity of the objective function. The curves show the mean objective function for the full dataset and for different rupture-distance bins. The dashed line denotes the global optimum of 0.29 Hz. The color version of this figure is available only in the electronic edition.

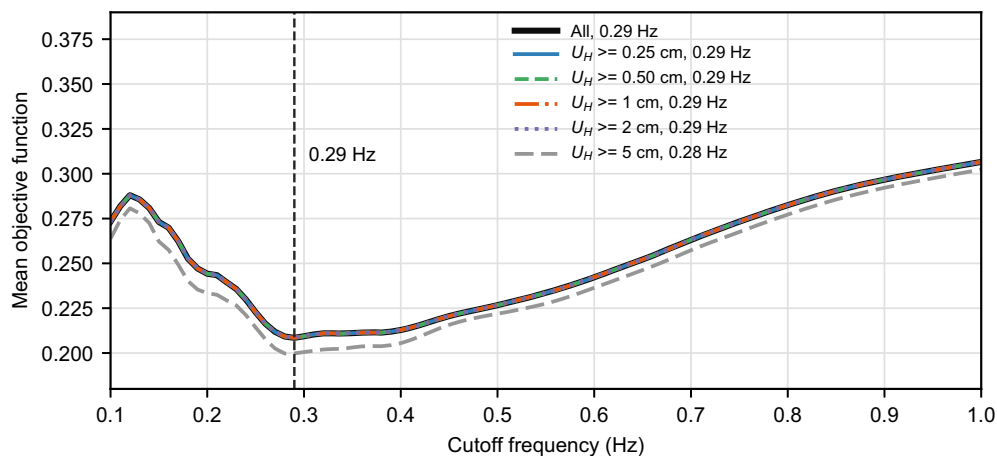


Figure 6. Sensitivity of the objective function to horizontal permanent-displacement amplitude. The curves compare the full dataset with station subsets retained after applying minimum horizontal permanent-displacement thresholds. The dashed line denotes the global optimum of 0.29 Hz. The color version of this figure is available only in the electronic edition.

at 0.29 Hz. These results indicate moderate distance-related variation, but the global cutoff remains a practical representative value for regional-scale decomposition over the dominant sample range.

We examined the influence of records with small permanent displacement, as shown in Figure 6. Horizontal static offsets were estimated from the final 5 s of each displacement record. We then recomputed the global objective function after retaining only stations with offsets aforementioned thresholds. The optimal cutoff remains 0.29 Hz for thresholds of 0.25, 0.50, 1.00, and 2.00 cm and changes only to 0.28 Hz when retaining only stations with offsets ≥ 5.00 cm. At this threshold, the objective-function increase at 0.29 Hz is only 0.03%. The offsets have

a median of 10.8 cm and a mean of 12.3 cm, indicating that most stations retain nonnegligible permanent displacement in the modeled near-fault regional field.

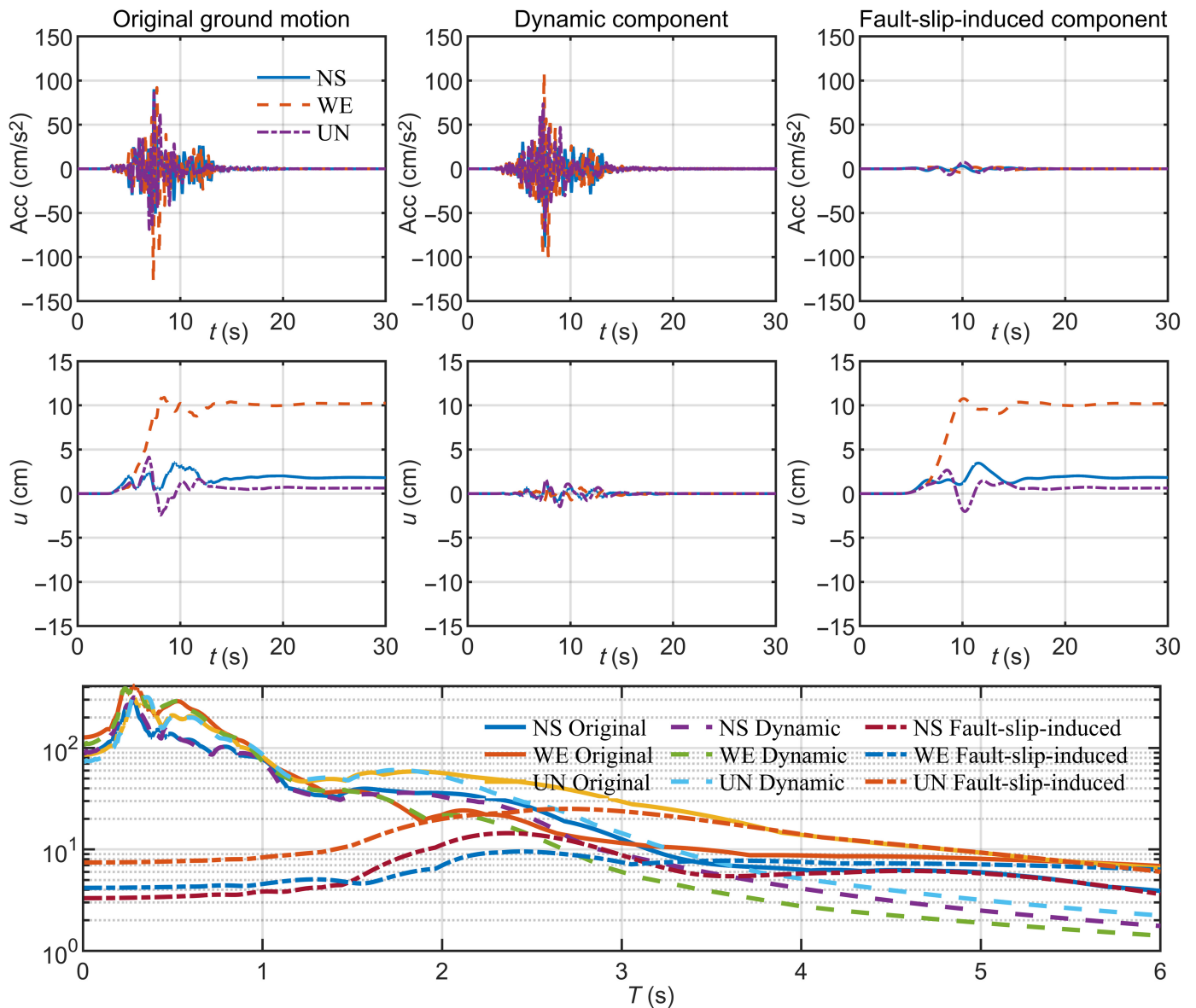
Verification of decomposition performance at the tunnel site

To verify the effectiveness of the proposed decomposition framework, representative ground-motion records are selected to compare the original signals with the decomposed dynamic and fault-slip-induced components in both time and frequency domains.

The first row of Figure 7 shows the acceleration time histories of the original ground motion, the dynamic component, and the fault-slip-induced component, respectively. It can be observed that the dynamic component retains the dominant acceleration peaks and waveform characteristics of the original signal, whereas the fault-slip-induced component contains negligible acceleration, indicating a clear separation of inertial effects. The second row shows the corresponding displacement time histories. The fault-slip-induced component successfully captures the permanent ground displacement,

exhibiting a clear residual displacement after the shaking phase. In contrast, the dynamic component oscillates around zero and does not contribute to permanent deformation. This confirms that the decomposition effectively distinguishes between displacement- and vibration-dominated behaviors.

The effectiveness of the decomposition is further evaluated using acceleration response spectra, as shown in the bottom panel of Figure 7. The dynamic component dominates the spectral amplitudes in the short-period range, whereas the fault-slip-induced component becomes more significant at longer periods. This trend is consistent with the physical characteristics of dynamic wave propagation and quasi-static fault deformation.



Overall, the results demonstrate that the proposed decomposition framework can effectively separate the dynamic and fault-slip-induced components while preserving their respective physical characteristics. The use of a unified cutoff frequency ensures that the decomposition remains consistent across different ground-motion records, which is essential for subsequent structural response analyses involving spatially distributed seismic inputs.

SPATIAL DISTRIBUTION CHARACTERISTICS OF DECOMPOSED MOTION COMPONENTS

Distribution of PGA, PGV, and PGD

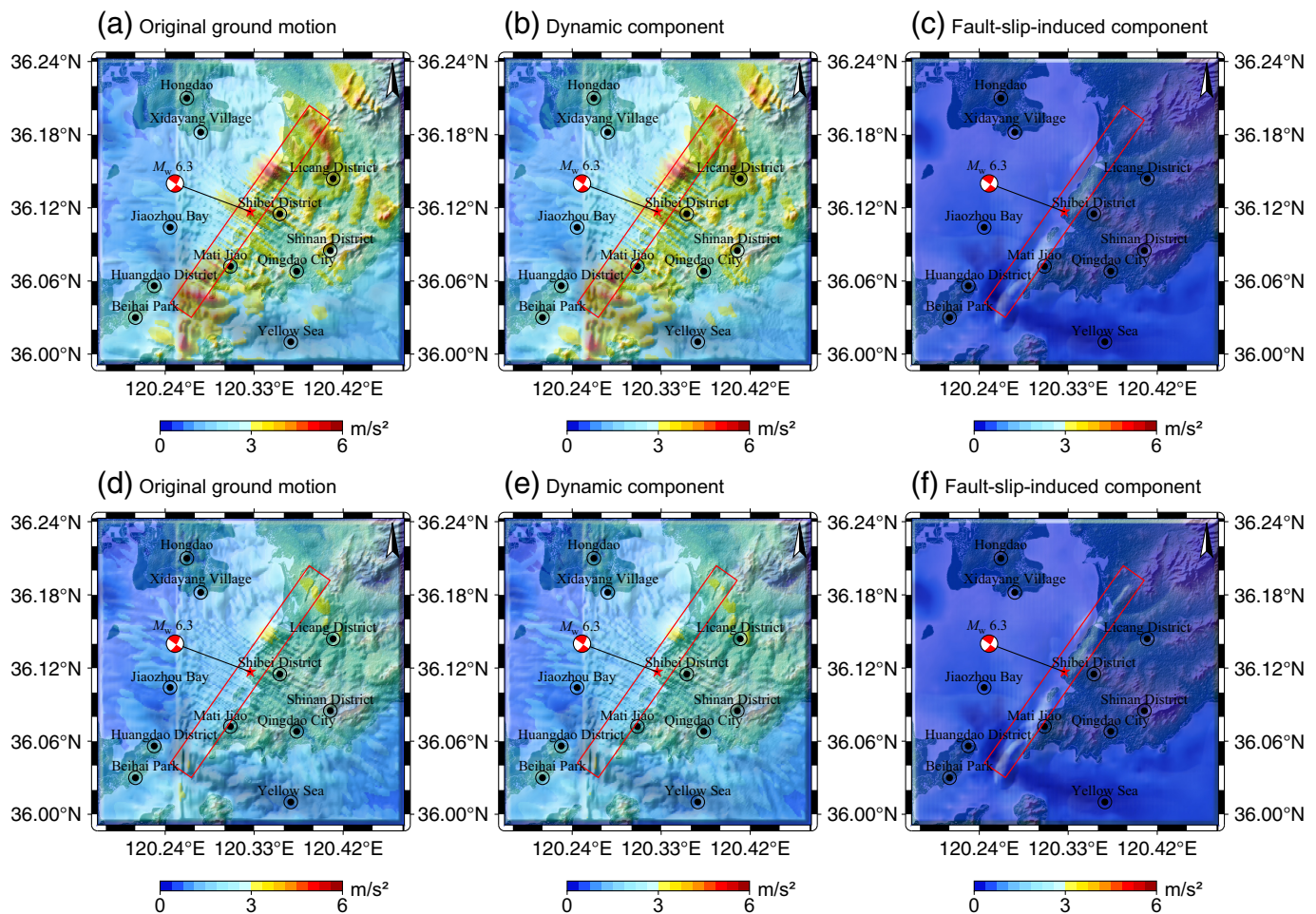
Figure 8 presents the spatial distributions of horizontal peak ground acceleration (PGA) for the original ground motion, the dynamic component, and the fault-slip-induced component at both the ground surface and a depth of 500 m below sea level.

It can be observed that the spatial distribution of PGA in the dynamic component is highly consistent with that

Figure 7. Acceleration, displacement, and acceleration response spectra of the original ground motion and its decomposed dynamic and fault-slip-induced components. The color version of this figure is available only in the electronic edition.

of the original ground motion, indicating that the dynamic component dominates the acceleration response. In contrast, the fault-slip-induced component exhibits negligible acceleration across the entire study area, confirming that the quasi-static fault deformation contributes minimally to inertial effects.

The PGA values are significantly amplified in the vicinity of the fault zone, particularly along the rupture direction, reflecting the strong influence of near-fault effects and rupture directivity. This amplification pattern is consistently captured in both the original and dynamic components, further demonstrating the effectiveness of the decomposition.



In addition, the comparison between surface and subsurface results shows that the spatial pattern of PGA remains generally consistent, although slight attenuation is observed with increasing depth. This suggests that the dynamic component governs the propagation of acceleration through the medium, whereas the fault-slip-induced component has a limited influence on acceleration-based seismic demand.

Depth-dependent variation of intensity measures

Figure 9 shows the spatial distributions of horizontal peak ground velocity (PGV) for the original ground motion and the decomposed components. Compared with PGA, the PGV distributions exhibit a more pronounced contribution from the fault-slip-induced component, especially in the vicinity of the fault.

The dynamic component still contributes significantly to PGV. However, the fault-slip-induced component becomes increasingly important in regions close to the fault trace, where permanent ground displacement is most pronounced. This indicates that velocity- and displacement-related seismic demands cannot be fully captured by the dynamic component alone.

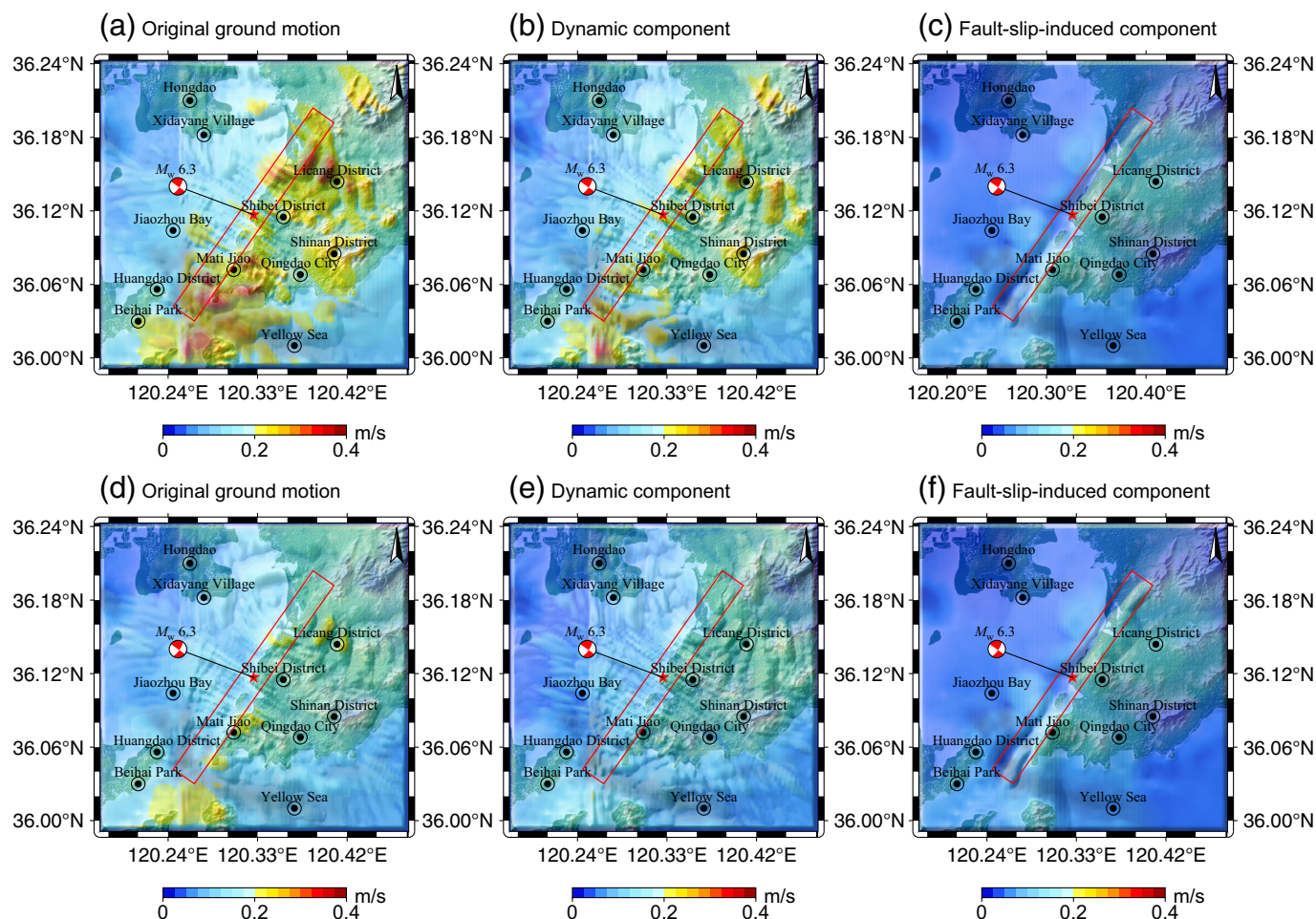
The spatial patterns of PGV reveal a clear concentration of high values along the fault zone, reflecting the combined effects of rupture propagation and permanent deformation. This

Figure 8. Spatial distributions of horizontal peak ground acceleration (PGA) for the original ground motion and decomposed components. (a–c) and (d–f) correspond to the ground surface and 500 m below sea level, respectively. Within each row, the left, middle, and right panels show the original ground motion, dynamic component, and fault-slip-induced component, respectively. The color version of this figure is available only in the electronic edition.

trend is more evident than that observed in PGA, highlighting the importance of considering fault-slip-induced components in near-fault seismic analyses.

Similar to the PGA results, the spatial distribution patterns at the ground surface and at a depth of 500 m remain generally consistent, suggesting that the decomposition framework is stable across different depths. However, the relative contribution of the fault-slip-induced component becomes more distinguishable in PGV, further emphasizing its role in displacement-related structural response.

These results highlight that although acceleration-based seismic demand is primarily governed by dynamic ground motion, velocity- and displacement-related responses are significantly influenced by fault-slip-induced components. Therefore, neglecting the latter may lead to an underestimation of structural demand in near-fault regions.



Surface displacement patterns in fault-parallel and fault-normal directions

Figure 10 presents the spatial distributions of peak ground displacement (PGD) for the original ground motion and the decomposed components at both the ground surface and a depth of 500 m below sea level.

It can be observed that the spatial distribution of PGD in the original ground motion is almost identical to that of the fault-slip-induced component. This indicates that the peak displacement is predominantly governed by fault slip, whereas the contribution from the dynamic component is negligible. The dynamic component exhibits very small displacement amplitudes across the entire study area, confirming that it primarily represents vibration-type motion without contributing to permanent ground deformation. In contrast, the fault-slip-induced component clearly captures the large displacement gradients concentrated along the fault zone, reflecting the permanent offset caused by fault rupture.

In addition, the comparison between surface and subsurface results indicates that the overall spatial pattern of displacement remains consistent with depth, although slight attenuation is observed. This further demonstrates the robustness of the proposed decomposition framework.

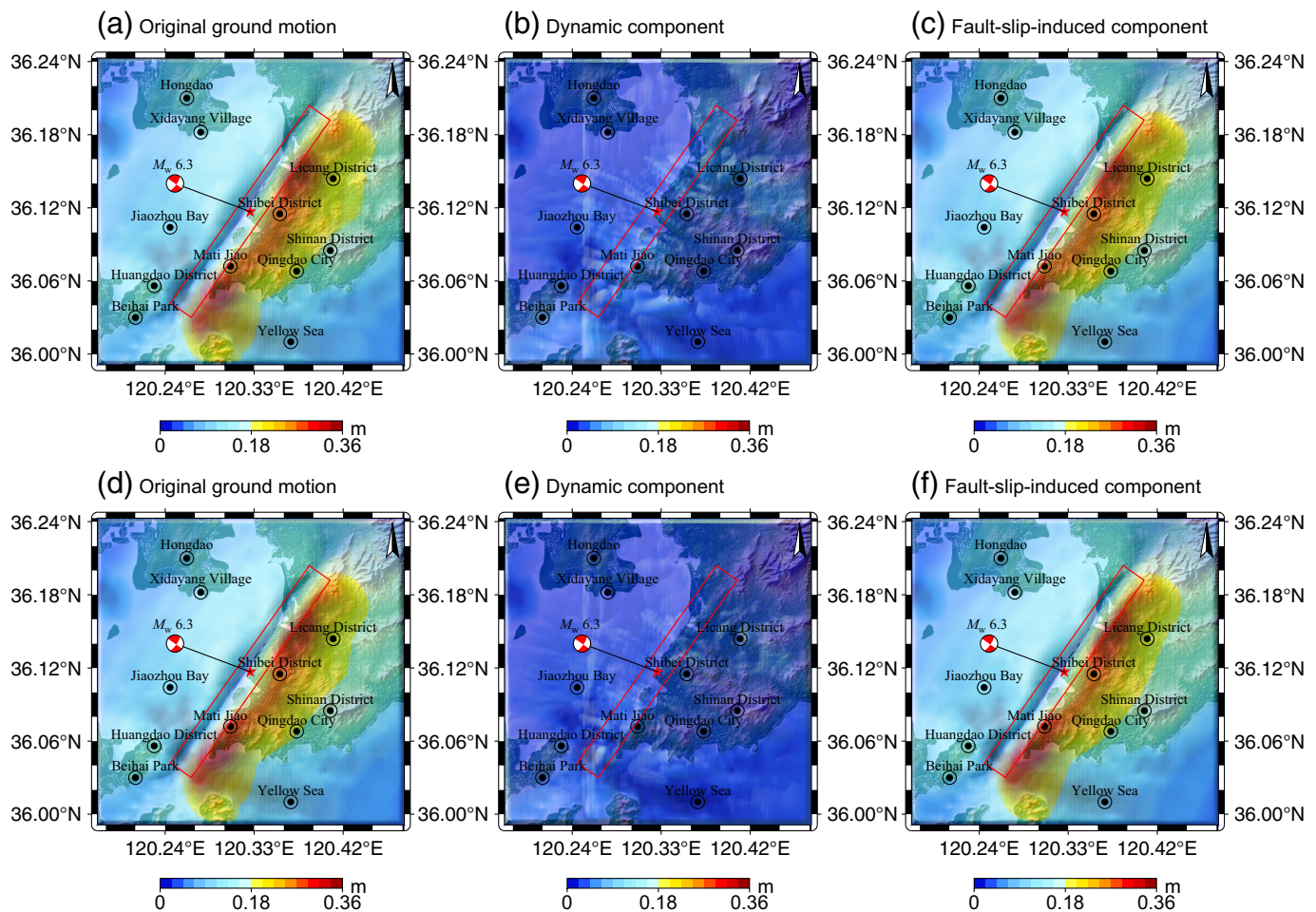
Figure 9. Spatial distributions of horizontal peak ground velocity (PGV) for the original ground motion and decomposed components. (a–c) and (d–f) correspond to the ground surface and 500 m below sea level, respectively. Within each row, the left, middle, and right panels show the original ground motion, dynamic component, and fault-slip-induced component, respectively. The color version of this figure is available only in the electronic edition.

These results highlight that unlike acceleration-based seismic demand, displacement-related responses in near-fault regions are almost entirely controlled by fault-slip-induced components. Therefore, accurate characterization of fault slip is essential for evaluating deformation demands of structures crossing active faults.

RESPONSE SPECTRAL CHARACTERISTICS AND ENGINEERING IMPLICATIONS

Fault-parallel spectral characteristics

Figure 11 presents the spatial distributions of acceleration response spectra in the fault-parallel direction for different periods, including 0.1, 1, 2, 3, 4, and 5 s. The results are shown for the original ground motion, the dynamic component, and the fault-slip-induced component.



At short periods (0.1–1 s), the spectral distributions of the dynamic component closely match those of the original ground motion, whereas the fault-slip-induced component exhibits negligible amplitudes across the entire study area. This indicates that the seismic response in this period range is dominated by dynamic ground motion associated with wave propagation and inertial effects.

As the period increases to the intermediate range (around 2–3 s), the contribution of the fault-slip-induced component becomes increasingly noticeable, particularly in the vicinity of the fault zone. Meanwhile, the spectral amplitudes of the dynamic component gradually decrease, indicating a transition in the dominant mechanism controlling the response.

At long periods (e.g., 3–5 s), the spectral distributions of the original ground motion become highly consistent with those of the fault-slip-induced component, whereas the dynamic component contributes only marginally. The high-spectral values are concentrated along the fault trace, reflecting the strong influence of permanent ground deformation induced by fault slip.

These results demonstrate a clear transition from dynamic-dominated behavior at short periods to fault-slip-induced dominance at long periods in the fault-parallel direction. This transition is particularly pronounced in near-fault

Figure 10. Spatial distributions of peak ground displacement (PGD) for the original ground motion and decomposed components. (a–c) and (d–f) correspond to the ground surface and 500 m below sea level, respectively. Within each row, the left, middle, and right panels show the original ground motion, dynamic component, and fault-slip-induced component, respectively. The color version of this figure is available only in the electronic edition.

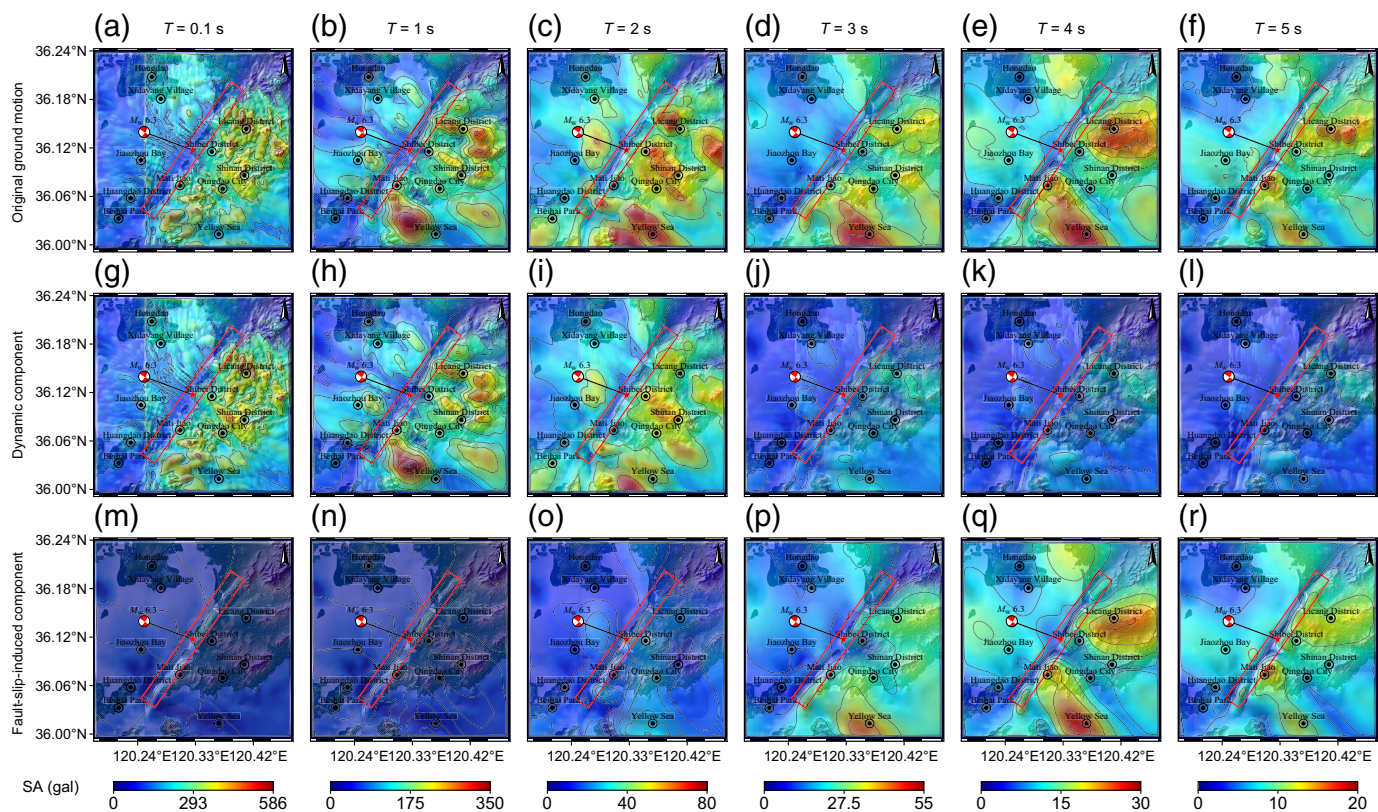
regions, where large permanent displacements significantly influence long-period structural response.

Fault-normal spectral characteristics

Figure 12 presents the spatial distributions of acceleration response spectra in the fault-normal direction for different periods, allowing a direct comparison with the fault-parallel results discussed earlier.

At short periods (0.1–1 s), the spectral distributions are dominated by the dynamic component, which closely matches the original ground motion. The fault-slip-induced component exhibits negligible contributions, similar to the behavior observed in the fault-parallel direction.

However, as the period increases, a notable difference emerges. In the intermediate-period range (around 2–3 s), the dynamic component remains the primary contributor, whereas the fault-slip-induced component shows only limited



influence. This contrasts with the fault-parallel direction, where the contribution of the fault-slip-induced component becomes significant in the same period range.

At long periods (3–5 s), although the fault-slip-induced component becomes more apparent, it does not fully dominate the spectral response. The dynamic component still contributes considerably across the study area. This indicates that the transition from dynamic-dominated to fault-slip-induced dominance is less pronounced in the fault-normal direction.

This directional difference can be interpreted from the component projection of near-fault motions for a strike-slip rupture. Because the slip vector of a strike-slip fault is approximately parallel to the fault strike, the coseismic permanent displacement, or fling-type displacement, is projected mainly onto the fault-parallel direction. Consequently, the fault-slip-induced component becomes increasingly important in the fault-parallel response at long periods. In contrast, the fault-normal component is more strongly influenced by dynamic radiation and rupture-directivity effects. Forward-directivity pulses in near-fault ground motions are long-period dynamic pulses and are commonly prominent in the fault-normal component of strike-slip events. Therefore, the dynamic component can remain significant in the fault-normal direction even at long periods. The observed direction-dependent decomposition is physically consistent with the strike-slip focal mechanism and with the different component projections of fling-type and directivity-related motions. Local variations in this pattern reflect the heterogeneous slip and rupture propagation in the stochastic rupture realization.

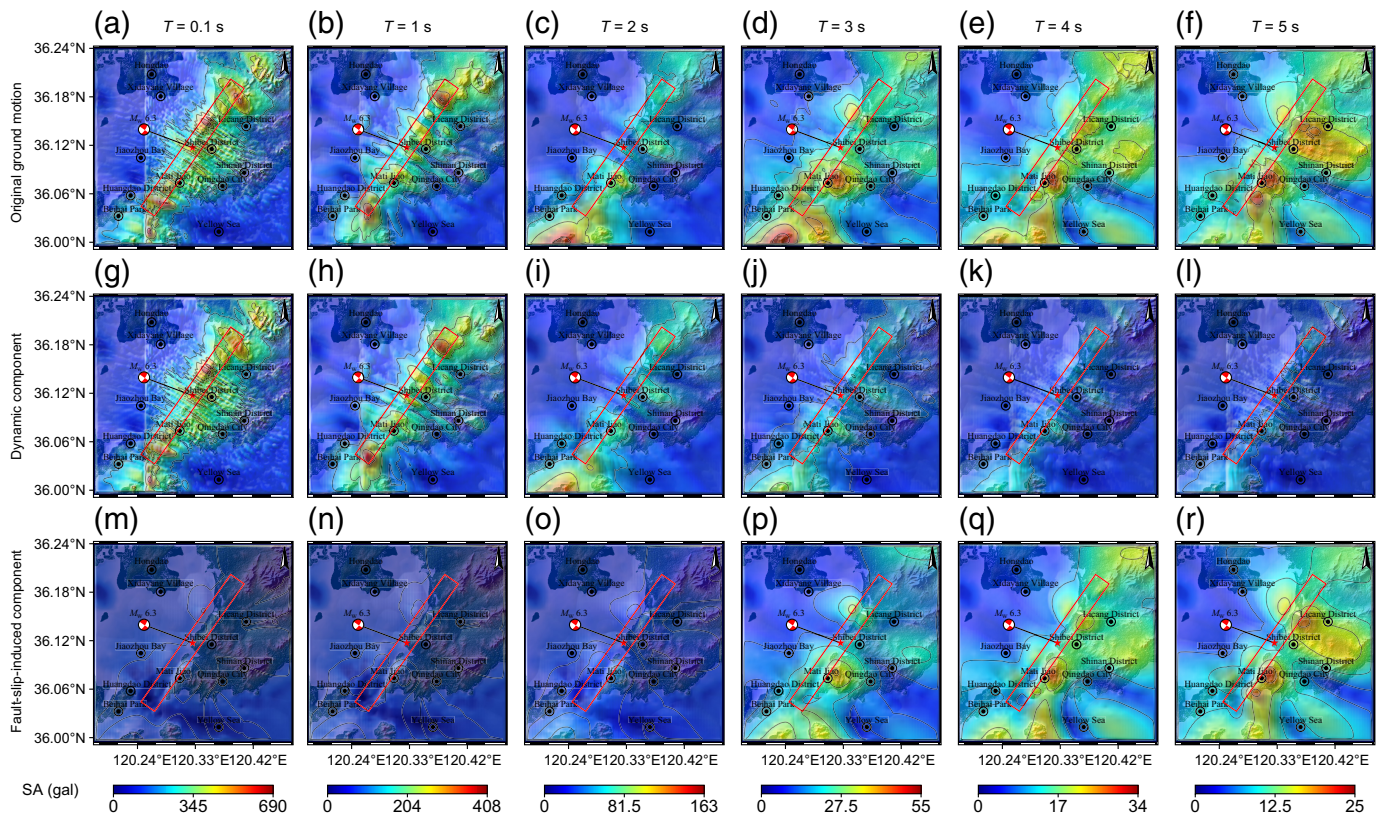
Figure 11. Spatial distributions of fault-parallel spectral acceleration for the original ground motion and decomposed components. (a)–(f), (g)–(l), and (m)–(r) show the original ground motion, dynamic component, and fault-slip-induced component, respectively. Within each row, the panels from left to right correspond to periods of 0.1, 1, 2, 3, 4, and 5 s, respectively. The color version of this figure is available only in the electronic edition.

These findings highlight that the directional characteristics of fault-induced deformation play a critical role in near-fault seismic response and should be explicitly considered in engineering analysis and design.

Transition of dominant effects from seismic motion to fault slip with increasing period

The fault-parallel and fault-normal spectral analyses reveal a period-dependent transition in the dominant mechanism controlling seismic response. The transition from dynamic-dominated to fault-slip-controlled behavior is observed with increasing structural period. This transition is pronounced in the fault-parallel direction, where fault-slip-induced components govern the long-period response, whereas it remains less significant in the fault-normal direction.

From an engineering perspective, the fault-slip-induced component should be explicitly considered for near-fault structures with medium to long natural periods, particularly those located close to or crossing active faults, because neglecting it may lead to substantial underestimation of displacement demand.



CONCLUSIONS

This study proposes a unified framework for decomposing regional ground motion into dynamic and fault-slip-induced components, with the objective of ensuring consistency in seismic input for near-fault structural analysis. The key findings are summarized as follows:

1. A regionally consistent decomposition method is developed based on an optimized cutoff frequency determined through a global objective function. This approach ensures that the decomposition is not dependent on individual ground-motion records, thereby providing a uniform basis for subsequent engineering analysis.
2. The spatial distributions of ground-motion components exhibit distinct characteristics. The dynamic component primarily governs acceleration-related responses, whereas the fault-slip-induced component dominates permanent ground displacement, especially in the vicinity of the fault zone.
3. A clear period-dependent transition in the dominant mechanism is identified. The seismic response is controlled by dynamic motion at short periods, whereas fault-slip-induced deformation becomes increasingly significant at long periods, particularly in the fault-parallel direction.
4. The influence of fault-slip-induced components shows strong directional dependency. The transition from dynamic to fault-slip dominance is more pronounced in the fault-parallel direction, whereas the dynamic component remains important in the fault-normal direction even at long periods.

Figure 12. Spatial distributions of fault-normal spectral acceleration for the original ground motion and decomposed components. (a)–(f), (g)–(l), and (m)–(r) show the original ground motion, dynamic component, and fault-slip-induced component, respectively. Within each row, the panels from left to right correspond to periods of 0.1, 1, 2, 3, 4, and 5 s, respectively. The color version of this figure is available only in the electronic edition.

Overall, the proposed framework provides a physically consistent and engineering-oriented approach for analyzing near-fault ground motion, highlighting the critical role of fault-slip-induced deformation in displacement-related seismic demand for near-fault structures.

DATA AND RESOURCES

The fault rupture model used in this study was generated using the Southern California Earthquake Center (SCEC) Broadband Platform (BBP), available at <https://github.com/SCECcode/bbp>. Regional ground-motion simulations were carried out using the SW4 finite-difference code, available at <https://github.com/geodynamics/sw4>. Some figures were prepared using the Generic Mapping Tools (GMT), available at <https://www.generic-mapping-tools.org>. All websites were last accessed in April 2026.

DECLARATION OF COMPETING INTERESTS

The authors acknowledge that there are no conflicts of interest recorded.

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