Reviewer Reports and Author Responses

Kearse et al., "Strong asymmetry in near-fault ground velocity during an oblique strike-slip earthquake revealed by waveform particle motions and dynamic rupture simulations"

Round 1

Reviewer B

The dynamic modeling of stations near the rupture fault is particularly intriguing, especially for those located above the main asperity on either side of the fault. Using forward dynamic rupture models, this study delves into the dynamics of the 2022 Chihshang earthquake, suggesting a shallow oblique slip direction with spatial variations marking asymmetry in near-fault ground motion on either side of the fault rupture. While the approach is interesting in seismology, the study in this article lacks comprehensiveness and crucial information. Several studies on the 2022 Chihshang earthquake, involving two active faults, namely the Central Range Fault (CRF) dipping to the west and the Longitudinal Valley Fault (LVF) dipping to the east, have been conducted. The primary rupture is from the western-dipping fault, with shallow rupture from the LVF contributing, as indicated by seismicity following the earthquake. The study in question argues against the LVF's involvement based on forward dynamic modeling but does not comprehensively consider other factors and stations.

The paper intriguingly models the stations pair of the 2022 Chishang earthquake, focusing on F073 and JPIN. However, it falls short in terms of station information, seismicity distribution, and examination of models from recent field surveys, especially concerning the eastern dipping LVF. The article lacks a seismicity map despite the earthquake sequence's high seismic activity. The manuscript mentions a station pair in the main asperity without defining its location or providing references. The opening statement in the introduction is criticized for not acknowledging other studies on near-fault ground motion in moderate earthquakes. Unfortunately, missing information, unclear sources, and references are noted throughout the text. IN conclusion, this study presents interesting modeling of the 2022 Chishang earthquake, it requires enhancements in terms of data completeness, referencing, and addressing other potential contributing factors to ground motion.

Some annotated comments.

1. The absence of a seismicity map in this article is notable, especially given the heightened seismic activity following the 20220917-20220918 earthquake sequence. It is imperative to include a plot illustrating the distribution of aftershocks, emphasizing how the interaction between the western-dipping fault (CRF) and the eastern-dipping fault (LVF) contributes to the seismic landscape.
2. The manuscript references a station pair within the main asperity, yet fails to provide any references or statements clarifying the location and definition of this asperity. It is crucial to include relevant information on the source and definition of the main

asperity, whether derived from field surveys or kinematic inversions, to enhance the clarity and credibility of the study.

3. In the introduction, the initial statement asserts that near-fault ground motion records from significant earthquakes usually exhibit substantial (>1 m/s) velocity pulses linked to permanent ground surface displacement. However, it is necessary to refine this opening statement, considering recent studies, such as Yen et al. (2021, BSSA), which indicate that near-fault effects can also be observed in moderate earthquakes, which apparently are under sub-shear rupture. (Yen, M.-H., S. von Specht, Y.-Y. Lin, F. Cotton, and K.-F. Ma (2021). Within- and Between-Event Variabilities of Strong-Velocity Pulses of Moderate Earthquakes within Dense Seismic Arrays, Bull. Seismol. Soc. Am. XX, 1–20,) doi: 10.1785/0120200376
4. L81, L86, there is a lack of clarity regarding the sensors used in the accelerometers. No sources are provided, and there is no reference mentioned.
5. On page 67, there's a reference to Ko et al., Fig. 1. Is this from Ko et al. (2023)?
6. At L72, the mention of being located above the main asperity lacks context. Please clarify how this main asperity is located and provide references supporting its identification.
7. At L97, in Fig. 2 A, why only the North component of velocity timeseries at strong-motion station G020 (red) is displayed.
8. L125, the time resolution of Stations F073 and JPIN? Basic information on this aspect is missing.
9. Vetter structure of the paper is needed. Clarification is needed on the role of Dc” to Dc in the modeling. Additionally, in section 2.2 discussing co-seismic displacement from optical images, the role of this map in the study is not well-defined. Consider incorporating this information as a reference rather than including it as a section in the paper.
10. Dc2 as Dc_2
11. L207 Why the authors did not consider a two-fault model, which has been observed in the field and other studies. It suggests the need for a discussion or exercise addressing the possibility of shallow motions from the eastern dipping fault as seen in seismicity, especially for the station JPIN.
12. L415 Long-period waves recorded at station HGSD are discussed, but there's a lack of citation to references supporting this statement. Additionally, further elaboration is needed on the argument for significant slip on the LVF.
13. Regarding F703 being on the hanging wall, mainly controlled by CRF, and JPIN being on the footwall of CRF but the hanging wall of the eastern dipping LVF, there's confusion about the waveforms not being well-explained in JPIN shown in Fig. 4A. The impression is that the study is intriguing with an important topic, but it lacks comprehensiveness in providing sufficient information and modeling. There's a mention of fault parallel large pulsive motion observed in sub-shear rupture from a dynamic modeling perspective, but it's noted that these observations could be also seen in moderate earthquakes. Clarification with more comprehensive references on this topic ais needed.

Reviewer A

Review:

Strong asymmetry in near-fault ground velocity during an oblique strike-slip earthquake revealed by waveform particle motions and dynamic rupture simulations

Summary

The authors combine an exceptional data set of a recent earthquake with smart dynamic modeling that reproduces ground motion asymmetry while introducing only a small number of free parameters.

The work is of high quality and certainly appropriate for publication in Seismica after minor revision. In particular, improving the discussion would benefit the study. My specific comments follow the structure of the manuscript.

Abstract:

The abstract well summarizes the exceptional data set, which is available for this earthquake, and the modeled ground motion asymmetry.

Line 29-31: "Observed near-fault, pulse-like fault-parallel ground velocity larger than fault-normal velocity can be explained by a model with a sub-shear rupture speed, which may be due to shallow rupture propagation within low-velocity material and to free surface reflections." - Please revise this sentence, a detailed explanation is given in my review of section 4.2.

The last sentence of the abstract is a bit vague.

Introduction:

The introduction is well written and briefly introduces the earthquake sequence, the tectonic setting, available data sets, and motivates for dynamic rupture modeling.

Data:

The section presents the data, associated processing, and methods in a clear manner and is easy to follow.

For subsection 2.4, please explain why you chose the fault-parallel component to estimate the slip-weakening distance and comment on how your assumption of an equal contribution from both sides of the fault could be affected by the observed asymmetry of displacements.

Dynamic rupture models of the Chihshang earthquake:

The authors might add that the effective normal stress assumes a hydrostatic pressure gradient.

Please provide more evidence that the drastic change in Dc is a realistic assumption. Alternatively, the higher Dc value at shallow depth could be discussed as a proxy for other effects, e.g., inelastic deformation or velocity-strengthening friction.

To enable reproducibility, all model parameters should be included in the manuscript. I cannot find the static friction coefficient and the prestress distribution.

Line 227-229: "..., dynamic stresses from reverse slip at depth cause the co-seismic slip direction to be oblique near the surface (Kearse & Kaneko, 2020), thereby reducing the along-dip contrast in rake angle in the final slip distribution.", that's an interesting aspect of your model that should be shown in a (supplementary) figure. Please add figures of your preferred single patch and multi patch dynamic rupture models to the supplementary material, showing, e.g., snapshots of the slip rate evolution and the final (strike/dip)-slip distribution.

The fault lengths of the single patch and the multi patch models in Fig. 3AB are different. If you use different fault geometries, there should be a clarification in the manuscript.

In line 264, you write about the multi patch model: "...our model is uniform along strike", which is not completely accurate.

Line 276-277: "..., which might signify a significant change in the width of the damaged zone", I am not convinced about the relation between Dc and fault zones from the provided references. Please add more references supporting this thesis or consider removing this interpretation.

Line 278: ".., we additionally vary seismic ratio (S-ratio) and …", you write about the S-ratio but the supplementary figure shows the prestress ratio, which is not the same. The text should be consistent with the figure.

Discussion and Coclusions:

Line 323-324: "This type of vertical stress distribution…", this phrasing might be a bit misleading, and could be replaced with, e.g., "Depth-dependent stress orientation".

Section 4.2 needs a revision. The observed fault-parallel velocity pulse is likely not the result of some complicated dynamic effect but the imprint of the static displacement near-field term and therefore limited to the direct vicinity of the fault. This effect is known as fling step, see e.g.:
Kalkan, E. and Kunnath, S.K. 2006. Effects of fling step and forward directivity on seismic response of buildings, Earthquake Spectra, 22(2), 367-90.

Section 4.3: Could you comment on the possibility of rupture on the east-dipping Longitudinal Valley fault (see Fig. 1 in Lee et al., 2023) contributing to the collapse of the Gaoliao bridge.

Section 4.4: Here, figures of the final slip distribution would be very helpful. I don't agree with your absolute inferences of Dc at shallow depth. I expect that the high Dc values produce a shallow slip deficit that is needed to fit the ground motions. But as mentioned above this could similarly be achieved by plastic deformation or velocity-strengthening friction. You should at least discuss the limitations of your elastic model.

Section 4.5: It seems that this section is highly speculative as your model is not well constrained where Lee et al. (2023) find slip on the LVF. I don't think that the fit at HGSD is good enough to conclude about slip on the LVF. In lines 418-420: "Similarly, the static offsets imaged by the GPS network do not resolve any change across the mapped surface trace of the LVF.", which stations do you mean here? Figure 3C does not show GPS stations at the relevant locations. The strength of your model is that it can explain the observed ground motion asymmetry despite its simplicity. I don't think that the study benefits from commenting on rather small-scale features.

Figures:

The figures generally are of high quality and well-chosen to support the manuscript. Figure 4 would be clearer with more space in between the subplots. Additional supplementary figures of the slip rate evolution and final slip distribution would benefit the manuscript.

Data and code availability:

Data and code are publicly available.

Minor Comments and Corrections:

- be consistent with using "Dc" or "D_c"
- line 39: replace "permeant" with "permanent"
- line 62: do you mean "from the epicenter" or "between the epicenter and ?"?
- caption Figure 1A: replace "within the Longitudinal Valley" with "within Taiwan"
- line 89: "numerically" redundant?
- caption Figure 3B: add a description of "JPIN model (5 km)"; replace "2 km depth" with "2 km down dip"
- caption Figure 3C: replace "grey vectors" with "black vectors"

Nico Schliwa
16 February 2024

Author response

We thanks both reviewers for their detailed and comprehensive reviews of our manuscript. In response to their comments and suggested changes, we have conducted additional dynamic rupture modelling of slip on the Longitudinal Valley Fault to assess its impact on near-fault ground motions at JPIN, produced 1 new figure for the main body of the article, and 5 new supplementary figures to support the findings of this study. We have made revisions to the text, and incorporated all minor suggested changes. Below is a detailed list of responses (in blue text) to the reviewers' comments (black text). Line numbers referenced in the responses refer to the revised manuscript, not the original submission.

Reviewer B:

The absence of a seismicity map in this article is notable, especially given the heightened seismic activity following the 20220917-20220918 earthquake sequence. It is imperative to include a plot illustrating the distribution of aftershocks, emphasizing how the interaction between the western-dipping fault (CRF) and the eastern-dipping fault (LVF) contributes to the seismic landscape.

We agree with the reviewers comment, and have included an additional supplementary figure (Fig. S1) that shows detailed aftershock distributions from the following article:

Sun, W. F., Pan, S. Y., Huang, C. M., Guan, Z. K., Yen, I. C., Ho, C. W., ... & Kuo-Chen, H. (2024). Deep learning-based earthquake catalog reveals the seismogenic structures of the 2022 MW 6.9 Chihshang earthquake sequence. *Terrestrial, Atmospheric and Oceanic Sciences*, *35*(1), 5.

We also use this figure to show that the LVF may have contributed to the mainshock ground motions, based on the seismicity occurring to the east of the LVF surface trace. We have included the following text to the article:

L62-25
"*Their models together with aftershock seismicity distributions (Sun et al., 2024) (Fig. S1) suggest that the east-dipping Longitudinal Valley Fault (LVF) also participated in the earthquake, with localised asperities (<10 km) reaching slip magnitudes of ~1 m.*"

The manuscript references a station pair within the main asperity, yet fails to provide any references or statements clarifying the location and definition of this asperity. It is crucial to include relevant information on the source and definition of the main asperity, whether derived from field surveys or kinematic inversions, to enhance the clarity and credibility of the study.

We have added the location of asperity to Fig. 1. This is defined as the section of the fault that has fault parallel slip of >1.5 m. We also include an additional supplementary figure (Fig. S2), which shows the distribution of surface horizontal slip derived from our optical imagery correlation. The location of the asperity in Figure 1 agrees with the location of a prominent asperity in the kinematic source inversion of Lee et al. (2023).

We add the following text to the article:

L72-75

"*In particular, we take advantage of a near-fault pair of sensors (250-3800 m from the fault) located on either side of the fault in the northern part of the rupture where surface slip is >1.5 m (we refer to this as the main asperity; black dashed line in Fig. 1)*."

In the introduction, the initial statement asserts that near-fault ground motion records from significant earthquakes usually exhibit substantial (>1 m/s) velocity pulses linked to permanent ground surface displacement. However, it is necessary to refine this opening statement, considering recent studies, such as Yen et al. (2021, BSSA), which indicate that near-fault effects can also be observed in moderate earthquakes, which apparently are under sub-shear rupture. (Yen, M.-H., S. von Specht, Y.-Y. Lin, F. Cotton, and K.-F. Ma (2021). Within- and Between-Event Variabilities of Strong-Velocity Pulses of Moderate Earthquakes within Dense Seismic Arrays, Bull. Seismol. Soc. Am. XX, 1–20,) doi: 10.1785/0120200376.

Following the reviewer's comments we made the opening sentence less broad, so as to only refer to fault-parallel velocity pulses that are associated with permanent fault offsets. This language makes the distinction between the example events we list in the introduction, and the moderate sized earthquakes discussed in Yen et al. (2021), such as the 2018 Mw 6.4 Hualien earthquake, where ground velocity pulses were neither fault-parallel nor were they associated with permanent offsets, and were instead characteristic of rupture directivity pulses. The opening sentence is now as follows:

L35-37

"*Near-fault ground motion records of large magnitude earthquakes (M>7.0) typically contain strong fault-parallel velocity pulses associated with permanent displacement of the ground surface.*"

L81, L86, there is a lack of clarity regarding the sensors used in the accelerometers. No sources are provided, and there is no reference mentioned.

We have provided additional information on the sensor type, and provided a reference:

L87-89

"*In order to derive velocity and displacement timeseries data from the strong motion accelerograms, we first remove the instrument response (instruments contain SMART24A sensors; Chen et al., 1994)*."

On page 67, there's a reference to Ko et al., Fig. 1. Is this from Ko et al. (2023)?

We have clarified that this refers to Ko et al. (2023)

At L72, the mention of being located above the main asperity lacks context. Please clarify how this main asperity is located and provide references supporting its identification.

We have addressed this issue above, where we have provided a clearer definition of this term.

At L97, in Fig. 2 A, why only the North component of velocity timeseries at strong-motion station G020 (red) is displayed.

We only show the north component in Figure 2A, as adding additional components would make the residual baseline drift in the north component less clear. We think that plotting the north component is sufficient to illustrate the problem of baseline drift, and to show the linear correction applied to the timeseries data.

L125, the time resolution of Stations F073 and JPIN? Basic information on this aspect is missing.

The sampling rate of sensors F073 (100 Hz) and JPIN (1 Hz) have been reported at lines 130 and 133

Better structure of the paper is needed. Clarification is needed on the role of Dc” to Dc in the modeling. Additionally, in section 2.2 discussing co-seismic displacement from optical images, the role of this map in the study is not well-defined. Consider incorporating this information as a reference rather than including it as a section in the paper.

We have included the following additional text to clarify the role of Dc” in the model setup:

L183-185

“We use this value of Dc” to inform our selection of slip-weakening distance for the shallow portion of dynamic rupture model (Dc_2).“

We have considered the reviewer’s suggestion regarding removing the optical image correlation results from the main text to the supplementary file. However, considering the central role of these data for (1) defining the orientation and extent of the main fault rupture for model setup and (2) measuring the distribution of surface slip and defining the location of the main asperity, we argue that it is best to keep this section in the article.

Dc2 as Dc_2

This correction has been applied.

L207 Why the authors did not consider a two-fault model, which has been observed in the field and other studies. It suggests the need for a discussion or exercise addressing the possibility of shallow motions from the eastern dipping fault as seen in seismicity, especially for the station JPIN.

L415 Long-period waves recorded at station HGSD are discussed, but there's a lack of citation to references supporting this statement. Additionally, further elaboration is needed on the argument for significant slip on the LVF.

Regarding F703 being on the hanging wall, mainly controlled by CRF, and JPIN being on the footwall of CRF but the hanging wall of the eastern dipping LVF, there's confusion about the waveforms not being well-explained in JPIN shown in Fig. 4A. The impression is that the study is intriguing with an important topic, but it lacks comprehensiveness in providing sufficient information and modeling. There's a mention of fault parallel large pulsive motion observed in sub-shear rupture from a dynamic modeling perspective, but it's noted that these observations could be also seen in moderate earthquakes. Clarification with more comprehensive references on this topic ais needed.

We think that the contribution of slip on the eastward-dipping LVF to the inferred ground motion asymmetry is relatively small and that our main conclusions should be unchanged regardless of the occurrence of minor LVF slip. To confirm this conjecture, we have set up and conducted additional dynamic rupture simulations of an isolated LVF that results in the approximate slip distribution shown in Tang et al. (2023). Note that including both CRF and LVF simultaneously in a dynamic rupture model would require significantly more work, which would not be needed to test this conjecture. We found that only limited (<15 cm) particle motion would be expected to occur at the location of JPIN. Based on this additional work, we argue that any potential slip on the LVF during the mainshock rupture does not affect the particle motions at JPIN, and does not influence the asymmetry in ground motion observed across the main rupture, which is the focus of this study. We have included additional supplementary figures (Figs. S8 and S9) that detail (1) the additional model setup, (2) the resulting slip distribution, and (3) particle motions at the location of JPIN. We have added the following text to the article:

L248-259

"Kinematic source models (Lee et al., 2023; Tang et al., 2023) and aftershock distributions (Fig. S1) of the Chihshang earthquake sequence suggest that slip on the northern part of the LVF near JPIN may have occurred during the mainshock rupture. Slip on the LVF may have contributed to the particle motions recorded at JPIN, which is located ~3 km above the east-dipping LVF plane (Fig. S10). We therefore conducted tests to assess the possible bias introduced by ignoring this contribution in our analysis.

We conducted dynamic rupture simulations of slip on an isolated, 70°-dipping 10x10 km fault patch, which results in the distribution of slip similar to the kinematic model of Tang et al. (2023) (i.e., 1 m of slip at ~8 km down dip distance, tapering to near zero slip at the free surface) (Fig. S11). The resulting particle motions at JPIN are small (<15 cm) (Fig. S10) compared to the observed particle motion (>1 m) demonstrating that slip of the LVF has little influence on ground motions at JPIN, and cannot explain the asymmetry in ground motions across the main surface rupture.”

Reviewer A (Nico Schliwa):

Line 29-31: “Observed near-fault, pulse-like fault-parallel ground velocity larger than fault-normal velocity can be explained by a model with a sub-shear rupture speed, which may be due to shallow rupture propagation within low-velocity material and to free surface reflections.” - Please revise this sentence, a detailed explanation is given in my review of section 4.2.

See response to review of section 4.2 below

The last sentence of the abstract is a bit vague.

We have added some more specific language to the last sentence:

L31-32

“*These results have important implications for near-fault ground-motion hazard*.”

For subsection 2.4, please explain why you chose the fault-parallel component to estimate the slip-weakening distance and comment on how your assumption of an equal contribution from both sides of the fault could be affected by the observed asymmetry of displacements.

We have included additional text to indicate the limitations of this assumption as applied to near-fault seismic data at F073:

L179-183

“*The assumption of symmetrical displacement on either side of the fault is not valid for this oblique-slip event, however we use the value of 0.9 m as derived from the fault parallel component, while acknowledging that this is only an approximation and represents a maximum estimate of D_c” (because the displacement should be larger on the hanging wall side than on the footwall side due to effect of the fault geometry) .*”

The authors might add that the effective normal stress assumes a hydrostatic pressure

We clarified the description as follows:

L203-205

Effective normal stress σ increases with depth via $\sigma = \rho g z(1-\lambda) = 10z$ (MPa), where g is gravity in m/s^2, density ρ = 2700 kg/m^3, z = distance along dip in km, and λ

= 0.62 is the fluid pressure ratio.

Please provide more evidence that the drastic change in Dc is a realistic assumption. Alternatively, the higher Dc value at shallow depth could be discussed as a proxy for other effects, e.g., inelastic deformation or velocity-strengthening friction.

We think that there is no resolution to infer a more precise distribution of Dc with depth. Hence we adopted this simple parameterization. As for an alternative interpretation, we have not tested inelastic deformation or velocity-strengthening friction, which remains a subject of future work. Please see the added text:

L459-464

"*We note that for simplicity, our dynamic rupture model assumes a slip-weakening friction law without accounting for velocity-strengthening friction at shallow depths (Kaneko et al., 2008) or off-fault plasticity (e.g., Andrews, 2005; Ma, 2008; Kaneko and Fialko, 2011). Examining how estimated* D_c *from simplified models, such as the one used in this study, may be influenced by these effects remains to be investigated.*"

To enable reproducibility, all model parameters should be included in the manuscript. I cannot find the static friction coefficient and the prestress distribution.

We agree with the reviewer's comment and have included additional clarity on these points:

L201-203

"*Model prestress magnitude and rake angle are uniform along strike and prestress magnitude increases linearly with depth*."

L212

"μ_s=0.67"

Line 227-229: "..., dynamic stresses from reverse slip at depth cause the co-seismic slip direction to be oblique near the surface (Kearse & Kaneko, 2020), thereby reducing the along-dip contrast in rake angle in the final slip distribution.", that's an interesting aspect of your model that should be shown in a (supplementary) figure. Please add figures of your preferred single patch and multi patch dynamic rupture models to the supplementary material, showing, e.g., snapshots of the slip rate evolution and the final (strike/dip)-slip distribution.

We agree with the reviewers suggestion and have included an additional supplementary figure (Fig. S9), and added the following text to the article:

L245-247

"*The evolution of slip rate and maps of final slip distributions for our preferred multi-patch model and the single-patch model are shown in Figure S9*.."

The fault lengths of the single patch and the multi patch models in Fig. 3AB are different. If you use different fault geometries, there should be a clarification in the manuscript.

We agree with the reviewer's comment and have included additional text that states the changes in fault length:

L233-235

"*To better match the observations we shortened the length of the multi-patch fault model from 50 to 46 km*. "

In line 264, you write about the multi patch model: "...our model is uniform along strike", which is not completely accurate.

We agree with the reviewer's comment and have modified the following sentence to reflect this:

L291-294

"*In addition, because our model fault geometry, frictional parameters, and velocity structure are uniform along strike, using data from a narrow along-strike window (<1 km) would reduce the influence on waveform misfit of any unmodelled along-strike heterogeneity in real fault properties between stations*."

Line 276-277: "..., which might signify a significant change in the width of the damaged zone", I am not convinced about the relation between Dc and fault zones from the provided references. Please add more references supporting this thesis or consider removing this interpretation.

Line 278: ".., we additionally vary seismic ratio (S-ratio) and ...", you write about the S-ratio but the supplementary figure shows the prestress ratio, which is not the same. The text should be consistent with the figure.

We have made the following correction:

L304-306

"With fixed D_{c2} and its depth extent as in the preferred model, we additionally vary non-dimensional prestress $\bar{\tau}^0 = (\tau^0 - \tau^d)/(\tau^s - \tau^d)$ (Kaneko and Lapusta, 2010) and fault frictional cohesion (Figs. S4a and S4b)."

Discussion and Conclusions:

Line 323-324: "This type of vertical stress distribution...", this phrasing might be a bit misleading, and could be replaced with, e.g., "Depth-dependent stress orientation".

We agree with the reviewer's comment, and thank them for their contribution; we have used this suggestion in the following sentence:

L351-354

"*This type of depth-dependent stress orientation favours reverse slip on a low-dipping fault at seismogenic depth, and oblique slip on a steeper fault surface at shallow depths, similar to our model of the Chihshang earthquake*."

Section 4.2 needs a revision. The observed fault-parallel velocity pulse is likely not the result of some complicated dynamic effect but the imprint of the static displacement near-field term and therefore limited to the direct vicinity of the fault. This effect is known as fling step, see e.g.: Kalkan, E. and Kunnath, S.K. 2006. Effects of fling step and forward directivity on seismic response of buildings, Earthquake Spectra, 22(2), 367-90.

We now mention in the introduction that the fault-parallel velocity pulse that we analyze indeed refers to the to the 'fling step' notion in earthquake engineering. While we acknowledge that the fling step is a well-known phenomenon, our focus here is to examine the mechanisms governingf its amplitude and duration (i.e., the characteristics of the fling step effect). To clarify, we have included an additional figure (Fig. 7) that compares on-fault slip at 6 km down dip distance to on-fault slip at the free surface. A combination of low wavespeeds at shallow depth, feedbacks between the rupture front and free surface reflections, and reflections from low-velocity layer boundaries together influence the slip rate at shallow depth, extending the period and duration of high slip rates. We suggest that the increased long-period slip envelope at shallow depth is responsible for the long-period high-velocity ground motions at near-fault locations. We modified the discussion in section 4.2 with reference to our new Figure 7:

L416-432

"*A near-fault, fault-parallel velocity pulse is often interpreted as the result of a fling step effect (Abrahamson, 2001; Kalkan and Kunnath, 2006) where near-fault displacement for a simple, Haskell source model becomes a ramp function with a rise time and the* *corresponding ground velocity becomes a box car function (Haskell, 1969), resulting in a pulse-like ground velocity. However, what controls the characteristics of the fling step effect (i.e., the amplitude and duration of a pulse-like ground velocity) still remains unclear. Our models show that at the free surface, large on-fault slip rates (>1 m/s) are sustained for longer time periods (~1 s), compared with slip at greater depth (<0.25 s at 6 km down dip distance) (Fig. 7). Large slip rates are maintained by the dynamic interaction of the propagating rupture and free surface which is enhanced by reflected shear waves from the boundaries of low-velocity layers, as shown by Kaneko and Goto (2022). In any case, we suggest that the period and amplitude of near-fault ground motions such as at F073 are the controlled by the dynamics of rupture propagation at shallow depth. In addition, shallow rupture speeds in excess of the low velocity material may also play a role in the production of enhanced fault-parallel ground motions (weak supershear signatures can be seen in Figs 5 and 6). More investigations are needed to fully untangle the various mechanisms that can enhance long-period near-fault ground motions."*

Section 4.3: Could you comment on the possibility of rupture on the east-dipping Longitudinal Valley fault (see Fig. 1 in Lee et al., 2023) contributing to the collapse of the Gaoliao bridge.

We have since completed additional modelling of slip on the LVF fault, and conclude that it would not have contributed significantly to the collapse of the Gaoliao bridge, we have added an additional sentence in this section to communicate this inference:

L387-389

"*Based on our models of ground motion due to slip on the Longitudinal Valley Fault (Figs. S8 and S9), we suggest that the LVF slip did not contribute much to the damage of the Gaoliao bridge*"

Section 4.4: Here, figures of the final slip distribution would be very helpful. I don't agree with your absolute inferences of Dc at shallow depth. I expect that the high Dc values produce a shallow slip deficit that is needed to fit the ground motions. But as mentioned above this could similarly be achieved by plastic deformation or velocity-strengthening friction. You should at least discuss the limitations of your elastic model.

To address the reviewer's comment, we have added the following sentences in Section 4.2:

L459-464

"*We note that for simplicity, our dynamic rupture model assumes a slip-weakening friction law without accounting for velocity-strengthening friction at shallow depths (Kaneko et al., 2008) or off-fault plasticity (e.g., Andrews, 2005; Ma, 2008; Kaneko and Fialko, 2011). Examining how estimated D_c from simplified models, such as the one used in this study, may be affected by these effects remains to be investigated."*

Section 4.5: It seems that this section is highly speculative as your model is not well constrained where Lee et al. (2023) find slip on the LVF. I don't think that the fit at HGSD is good enough to conclude about slip on the LVF. In lines 418-420: “Similarly, the static offsets imaged by the GPS network do not resolve any change across the mapped surface trace of the LVF.”, which stations do you mean here? Figure 3C does not show GPS stations at the relevant locations. The strength of your model is that it can explain the observed ground motion asymmetry despite its simplicity. I don’t think that the study benefits from commenting on rather small-scale features.

We agree with the reviewer that the fit at station HGSD alone is not enough to conclude about slip on the LVF, but this is actually what Lee et al (2023) argued. What we are stating here is that there is no evidence of significant slip on the LVF from the fit to the HGSD waveforms. To address the reviewer comment, we have clarified the relevant sentences

L467-479

“Our earthquake rupture model reproduces the static and dynamic geodetic pattern of deformation within Longitudinal Valley without including the secondary, east-dipping Longitudinal Valley Fault (LVF). However, there are reports of ground surface rupture (up to ~20 cm offsets) across the mapped trace of the LVF at the time of the mainshock rupture (Ko et al., 2023). Lee et al. (2023) modelled the Chihshang mainshock earthquake as a west-dipping fault source (similar to our model) but with simultaneous rupture of the east-dipping LVF that contributed 17% of the total seismic moment of this event. Long-period waves recorded at station HGSD, located to the northeast and beyond the extent of our imaged fault source (Fig. 1) were used to argue for significant slip on the LVF (Lee et al., 2023), yet our source model results in ground motions there that match those recorded by HGSD (Fig. S5), suggesting slip on the LVF may not be required to explain the HGSD waveforms. Although it is likely that slip of <1 m did occur on the LVF, the near-fault strong-motion and geodetic data that we have analysed do not show clear signals from the LVF slip.”

Additional supplementary figures of the slip rate evolution and final slip distribution would benefit the manuscript.

We agree with the reviewer’s comments and have produced the suggested figures. See above responses.

Minor Comments and Corrections:

- be consistent with using “Dc” or “Dc”

- line 39: replace “permeant” with “permanent”

- line 62: do you mean “from the epicenter” or “between the epicenter and ?”?

- caption Figure 1A: replace “within the Longitudinal Valley” with “within Taiwan”

- line 89: “numerically” redundant?

- caption Figure 3B: add a description of “JPIN model (5 km)”; replace “2 km depth” with “2 km down dip”

- caption Figure 3C: replace “grey vectors” with “black vectors”

All suggested minor corrections have been implemented.

Round 2

Reviewer B

The revised manuscript had addressed most of the queations or comments.

The minor comments pertain to the content in abstract and introduction. Please specify the number of near-fault stations referred to in his paper, as from my understanding, the modeling does not encompass all of the near-fault stations.

Reviewer A

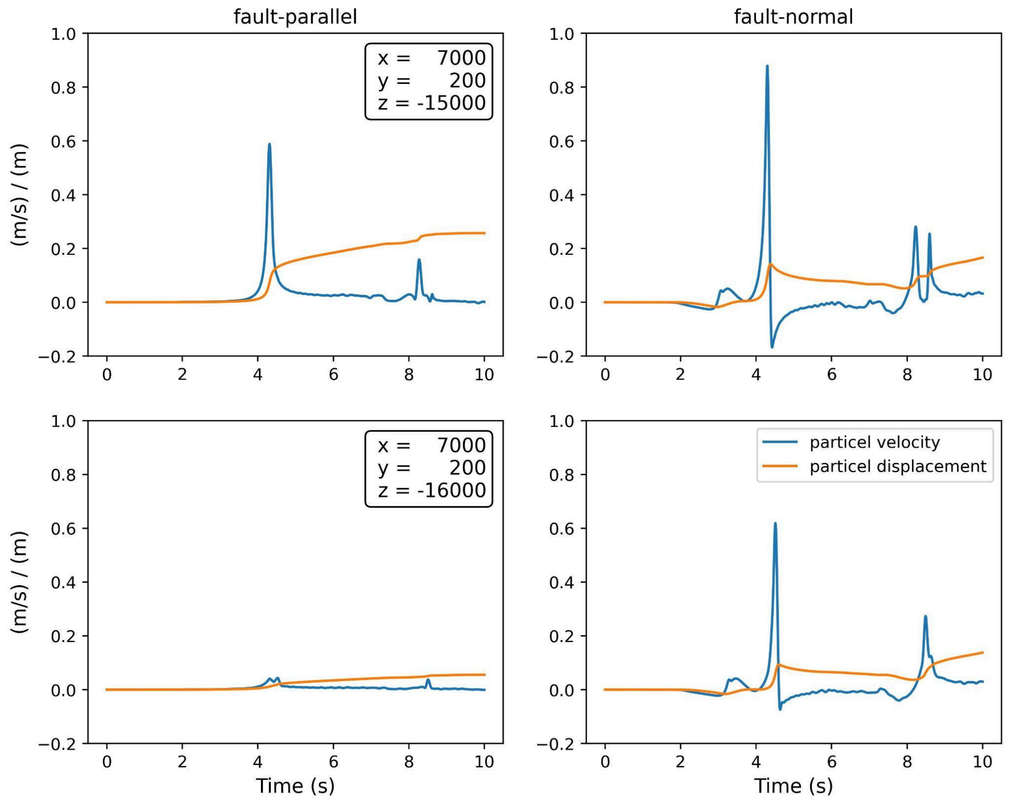
Second review:

Strong asymmetry in near-fault ground velocity during an oblique strike-slip earthquake revealed by waveform particle motions and dynamic rupture simulations

Thanks to the authors for already addressing many reviews. I still have a few minor complaints. After addressing them, the manuscript is ready for publication.

My main issue with the current manuscript is that you still are not clear enough that static displacement near-field terms are the generation mechanism of the observed fault-parallel velocity pulses. The free surface reflections are secondary effects that prolong the (fault-)slip duration and induce a healing front.

To demonstrate this, I ran a modified TPV-5 setup with homogeneous prestress of 70 MPa outside of the nucleation patch, and put some receivers at the bottom of the fault:



The first receiver is located 200 m in y-direction away from the bottom of the fault. The second receiver is located 1000 m deeper than the first receiver. The first receiver exhibits a considerable velocity pulse due to the static displacement. This pulse nearly completely vanishes for the second receiver, due to the fast decaying nature of the near-field terms. In contrast, the fault-normal components of both receivers differ much less. This demonstrates that no free surface or low-velocity zone effects are needed to generate such a fault-parallel pulse. However, in reality, this effect is always observed in combination with the free surface effect, as we only have observations this close to the source for stations next to surface-breaking ruptures.

Mainly, I want the static displacement to be acknowledged as the generation mechanism in this sentence of the abstract:
“Observed near-fault, pulse-like fault-parallel ground velocity larger than fault-normal velocity can be explained by a model with a sub-shear rupture speed, which may be due to shallow rupture propagation within low-velocity material and to free surface reflections.”

L416-420: “A near-fault, fault-parallel velocity pulse is often interpreted as the result of a fling step effect (Abrahamson, 2001; Kalkan and Kunnath, 2006) where near-fault displacement for a simple, Haskell source model becomes a ramp function with a rise time and the corresponding ground velocity becomes a box car function (Haskell, 1969), resulting in a pulse-like ground velocity.”

What does “is often interpreted as” mean? Please be clear that static displacement will cause a fault-parallel velocity pulse and this is not only a feature of a simple theoretical model.

Minor comments:

L197-199: “Since Dc is proportional to the fracture energy and may be related to the width of a fault damage zone and decrease with depth (e.g., Ide & Takeo, 1997).” I still think that the relation between Dc and fault damage zone width is highly speculative

L202: Please add here explicitly how you compute the prestress magnitude. At the moment, it’s hidden in the Supplements

L204: z is defined as the distance along dip, but I suppose it’s depth? Otherwise, the definition of normal stress does not work.

Figure S9: exhibits numerical oscillations. As far as I know, they always occur when modeling dynamic rupture with a spectral element method, but some damping procedure is usually used to remove them. Or are these resolution issues? Please comment on that in the figure caption

L427: remove “the”

Best regards,
Nico Schliwa

10 June 2024

Author Response

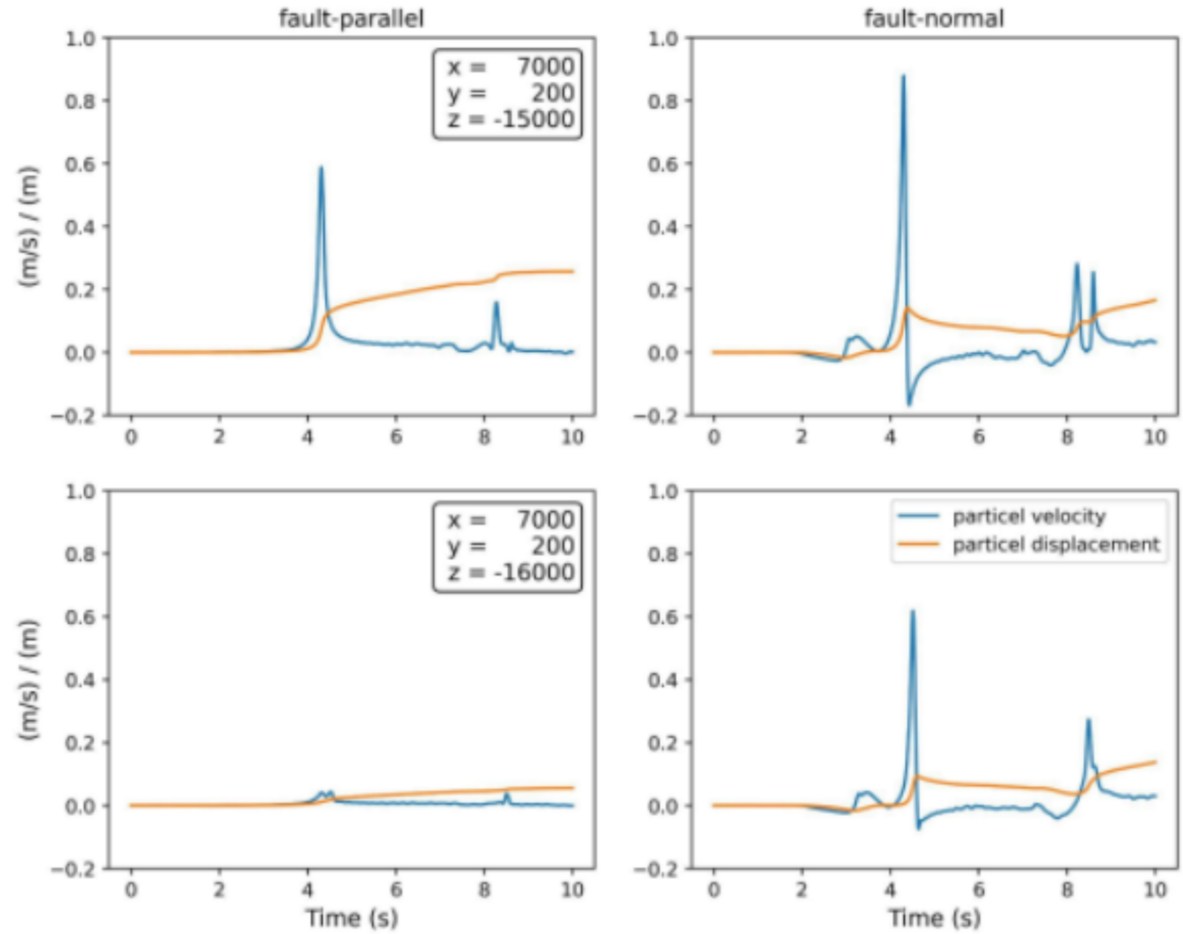
Response to Reviewers

We thank the Editor and both reviewers for their reviews of our manuscript. We have further revised the manuscript to address the reviewers' comments, which has resulted in minor modification of some of the text in the introduction and discussion sections, mainly relating to Reviewer A's comments.

Reviewer A: Nico Schliwa

My main issue with the current manuscript is that you still are not clear enough that static displacement near-field terms are the generation mechanism of the observed fault-parallel velocity pulses. The free surface reflections are secondary effects that prolong the fault-slip duration and induce a healing front.

To demonstrate this, I ran a modified TPV-5 setup with homogeneous prestress of 70 MPa outside of the nucleation patch, and put some receivers at the bottom of the fault:



The first receiver is located 200 m in y-direction away from the bottom of the fault. The second receiver is located 1000 m deeper than the first receiver. The first receiver exhibits a considerable velocity pulse due to the static displacement. This pulse nearly completely vanishes for the second receiver, due to the fast decaying nature of the near-field terms. In contrast, the fault-normal components of both receivers differ much less. This demonstrates that no free surface or low-velocity zone effects are needed to generate such a fault-parallel pulse. However, in reality, this effect is always observed in combination with the free surface effect, as we only have observations this close to the source for stations next to surface-breaking ruptures.

Mainly, I want the static displacement to be acknowledged as the generation mechanism in this sentence of the abstract:

"Observed near-fault, pulse-like fault-parallel ground velocity larger than fault-normal velocity can be explained by a model with a sub-shear rupture speed, which may be due to shallow rupture propagation within low-velocity material and to free surface reflections."

Reviewer A seems to have misunderstood what we are discussing in our study. We agree that it is well understood that the fault-parallel velocity pulse is indeed dominated by the static effect. However, the specific point we are focusing on in this paper is the ***enhanced*** fault-parallel velocity pulses, where the amplitude of the fault parallel component ***exceeds*** the amplitude of the fault normal component, and where the period of the pulse is also enhanced. This is stated in the above quoted sentence in the abstract.

"Observed near-fault, pulse-like fault-parallel ground velocity larger than fault-normal velocity can be explained by a model with a sub-shear rupture speed, which may be due to shallow rupture propagation within low-velocity material and to free surface reflections."

To emphasise this point more clearly in the relevant part of the discussion, we have included the following text:

"While the fault-parallel velocity pulse is dominated by the static effect at near-field locations, the factors controlling the amplitude and period of the fling step still remain unclear."

We are confident that the above added text will avoid any further confusion.

L416-420: "A near-fault, fault-parallel velocity pulse is often interpreted as the result of a fling step effect (Abrahamson, 2001; Kalkan and Kunnath, 2006) where near-fault displacement for a simple, Haskell source model becomes a ramp function with a rise time and the corresponding ground velocity becomes a box car function (Haskell, 1969), resulting in a pulse-like ground velocity."

What does "is often interpreted as" mean? Please be clear that static displacement will cause a fault-parallel velocity pulse and this is not only a feature of a simple theoretical model.

We agree with this comment and have removed the word "often".

Minor comments:
L197-199: "Since Dc is proportional to the fracture energy and may be related to the width of a fault damage zone and decrease with depth (e.g., Ide & Takeo, 1997)." I still think that the relation between Dc and fault damage zone width is highly speculative.

We have removed this conjecture from the paper.

L202: Please add here explicitly how you compute the prestress magnitude. At the moment,
it's hidden in the Supplements

We have added the following clarifying text:

"As a result, both the static (τ_s) and dynamic (τ_d) strength as well as the magnitude of initial shear stresses τ_0 linearly increase with depth ($\tau_0 = 0.55\sigma$)."

L204: z is defined as the distance along dip, but I suppose it's depth? Otherwise, the definition of normal stress does not work.

We have modified the equation to reflect the dip angle of the fault:

"Effective normal stress σ increases with depth via $\sigma = \rho g z \sin(\delta)(1-\lambda) = 10z$ (MPa), where δ is fault dip angle in degrees, g is gravity in m/s^2, density $\rho = 2700\ kg/m^3$, z = distance along dip in km, and $\lambda = 0.62$ is the fluid pressure ratio."

Figure S9: exhibits numerical oscillations. As far as I know, they always occur when modeling dynamic rupture with a spectral element method, but some damping procedure is
usually used to remove them. Or are these resolution issues? Please comment on that in the
figure caption.

We have added the following sentence in the caption of Figure S9:

"*Numerical oscillations are due to the marginal resolution of the fault model*"

L427: remove "the"

We have removed this word.

Reviewer B:

Please specify the number of near-fault stations referred to in his paper, as from my understanding, the modeling does not encompass all of the near-fault stations.

We have added the following clarifying text:

"In contrast to previous studies that focused on the broad aspects of the Chihshang earthquake, we focus on the near-fault ground velocities captured by three strong-motion and six 1-Hz GPS sensors (Fig. 1)."