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Title: Hybrid implicit–explicit XFEM simulation of injection-induced seismicity: resolving multi-scale rupture nucleation and dynamics

Dear Dr. Moulas,

We sincerely thank you for your careful assessment of our revised manuscript and for recognizing the potential contribution of the proposed hybrid implicit–explicit solution strategy. We particularly appreciate your constructive comments regarding temporal convergence and the reliability of the reference solution used to evaluate the hybrid formulation.

We fully agree that the differences in rupture onset time and propagation speed between the fully implicit simulations with minimum time steps of 10^{-4} and 10^{-5} s in the previous version were significant relative to the short duration of the seismic event. Consequently, the use of the 10^{-4} s simulation as the reference for evaluating the hybrid approach was not sufficiently justified.

In response to your comment, we have carefully re-examined our numerical results and substantially revised the convergence analysis and subsequent comparisons. During this reassessment, we also identified a problem affecting the nucleation timing in the previously reported fully implicit simulation with a minimum time step of 10^{-5} s and in the hybrid simulations. This issue has now been corrected, and the affected simulations and corresponding comparisons have been updated. We apologize for this inconsistency in the previous manuscript.

To address your comment and ensure the accuracy and consistency of the reported results, we have made the following revisions to the manuscript, all of which are highlighted in blue in the revised version:

1. Extended temporal-convergence assessment

As requested, we have extended the fully implicit convergence analysis by including an additional simulation with a minimum time step of 10^{-6} s. The revised Figure 7 now compares four minimum time-step sizes: 10^{-3}, 10^{-4}, 10^{-5}, and 10^{-6} s.

The updated results demonstrate that the solutions obtained with 10^{-5} and 10^{-6} s are nearly indistinguishable in terms of rupture-onset behavior, average accumulated slip, seismic moment, moment magnitude, and spatial rupture-speed distribution. In contrast, the 10^{-4} s simulation still exhibits noticeable differences, confirming that this time-step size does not provide sufficient temporal resolution for all the investigated dynamic quantities. These findings indicate that the fully implicit solution has effectively converged at a minimum time step of 10^{-5} s for the reported observables on the adopted spatial mesh. Accordingly, we have selected this solution as the new reference for evaluating the hybrid formulation. We have also clarified that the observed temporal convergence does not establish mesh-independent accuracy.

2. Revised comparison between the fully implicit and hybrid approaches

Following the convergence assessment and correction of the nucleation-timing issue, we have updated the hybrid simulations and their comparison with the fully implicit reference. Both approaches now employ a minimum time-step size of 10^{-5} s, with the hybrid formulation using a fixed mechanical time step of 10^{-5} s during its central-difference integration phase.

Consequently, Figures 8–11 and the corresponding discussions in Section 4.2 have been revised to reflect the updated reference and hybrid solutions.

Importantly, the revised results provide a more balanced assessment of the agreement between the two integration strategies. Although the hybrid approach successfully reproduces the overall rupture sequence, stress evolution, final accumulated slip, and seismic moment, noticeable differences remain in certain transient dynamic characteristics. In particular, the hybrid solution generally predicts delayed and lower peak slip velocities and lower rupture-propagation speeds compared with the fully implicit solution. Differences are also observed in transient particle acceleration and velocity amplitudes.

Nevertheless, both formulations predict nearly identical final average slip values of approximately 0.041 m and comparable moment magnitudes of approximately 1.5. We have therefore revised the discussion to distinguish agreement in final event-scale quantities from agreement in transient rupture dynamics, rather than presenting the two approaches as having equivalent dynamic accuracy.

3. Updated computational-performance assessment and conclusions

Using the temporally converged fully implicit reference has also required us to revise the computational-performance assessment. The fully implicit simulation with a minimum time step of 10^{-5} s requires approximately 26.4 h, whereas the hybrid simulation with a switching slip-velocity threshold of 0.01 m/s requires approximately 10.0 h. This corresponds to a computational-time reduction of 62.12%.

Accordingly, the previously reported computational savings of approximately 60–70% have been revised to approximately 46–62%, depending on the switching threshold.

We have also updated the Abstract, Section 4.1, Section 4.2, and the Conclusions to reflect the extended convergence assessment and the revised comparisons. In particular, we now emphasize that the temporal resolution required for accurate dynamic rupture simulation can be substantially smaller than the wave-speed-based explicit stability estimate, even when an unconditionally stable implicit time-integration scheme is employed.

4. Removal of the previous Section 4.3

During preparation of the revised manuscript, we also reconsidered the comments raised in the previous review round. The former Section 4.3 examined mesh and explicit-phase parameter sensitivities to help explain the previously reported rupture-timing differences. After correcting the nucleation-timing issue, the fully implicit and hybrid simulations now show much closer agreement in rupture initiation time. Because the former sensitivity results were based on superseded simulations, we removed this section to avoid presenting comparisons inconsistent with the corrected reference. The remaining discrepancies in transient rupture dynamics are discussed in Section 4.2, and the need for further systematic mesh-refinement studies is acknowledged in Section 6.

We believe that these revisions directly address your central concern regarding temporal convergence and provide a more reliable and transparent evaluation of the proposed hybrid strategy.

We sincerely appreciate your guidance, which has helped us improve the numerical reliability, scientific interpretation, and overall quality of the manuscript. We hope that the revised manuscript satisfactorily addresses your concerns and is now suitable for further consideration in *Geoscientific Model Development*.

Kind regards,

Mohammad Sabah
On behalf of all co-authors