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Supplement of

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

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The benchmark tests presented in Sections S1–S3, which verify the fully implicit solution approach, were previously reported and discussed in detail in Sabah et al. (2026). For completeness, a concise summary of the benchmark configurations and main verification results is provided in the Supplementary Information of the present study. Section S4 presents an additional benchmark used to verify the explicit dynamic component of the proposed solution approach.

S1. Consolidation problem without discontinuity

This benchmark was used to verify the hydromechanical coupling in a saturated porous medium without internal discontinuities. The problem consists of a 15 m × 1 m plane-strain rectangular domain subjected to a compressive stress of 10 kPa on the left boundary (Fig. S1). Horizontal displacement is constrained on the lateral boundaries, while vertical displacement is constrained at the top and bottom boundaries. The left boundary is drained by prescribing zero pore pressure, whereas the remaining boundaries are impermeable. The domain was discretized using bilinear quadrilateral elements with a uniform element size of 0.15 m. The computed pore-pressure and displacement responses were compared with the analytical consolidation solution based on Terzaghi's theory (Wang, 2000). The numerical and analytical pressure and displacement profiles at selected time steps are compared in Figure S2. The results show good agreement, confirming that the model accurately reproduces the coupled pore-pressure dissipation and mechanical deformation expected for this consolidation benchmark.

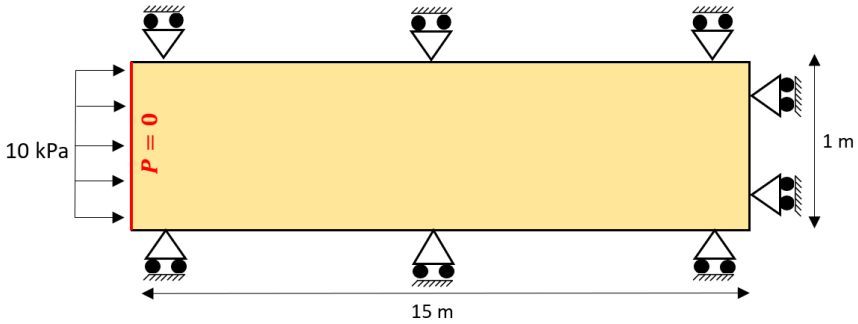


Figure S1. Schematic representation of the consolidation benchmark: a 15 m × 1 m saturated porous domain subjected to a uniform compressive stress of 10 kPa on the drained left boundary. The lateral boundaries are horizontally constrained, while the top and bottom boundaries are vertically constrained and hydraulically impermeable.

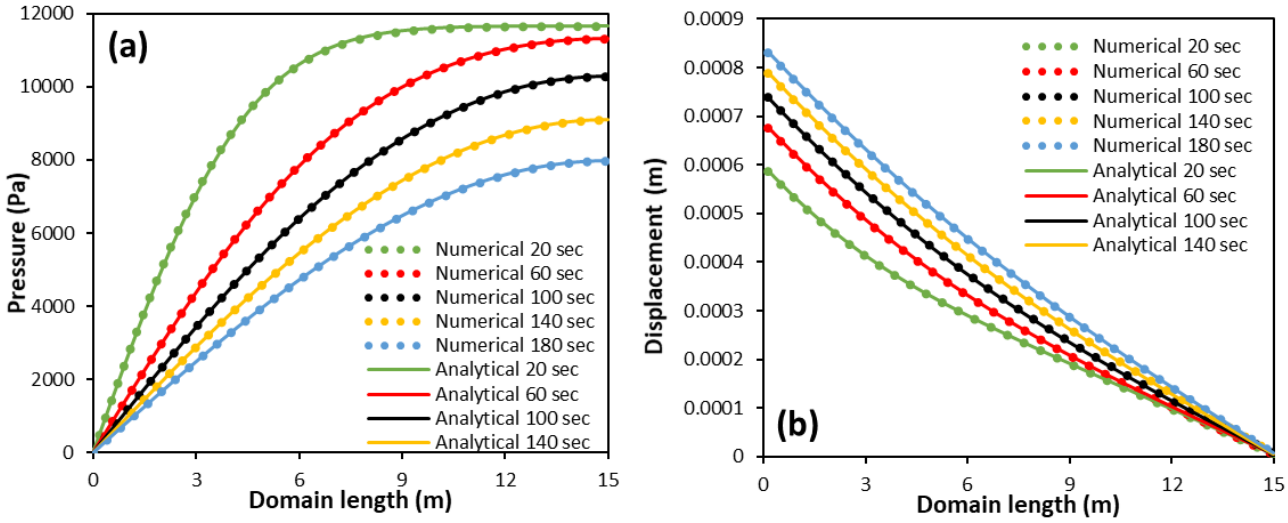


Figure S2. Comparison of numerical and analytical solutions for (a) pore pressure distribution and (b) displacement along the domain length at different time steps: 20 s, 60 s, 100 s, 140 s, and 180 s.

S2. Consolidation problem with discontinuity

The second benchmark examines hydromechanical consolidation in a fractured porous medium. The model consists of a 10 m × 20 m plane-strain domain containing a 12 m long horizontal fracture at the center (Fig. S3), with an initial aperture of 5 mm. Displacement normal to the external boundaries is constrained, and a uniform compressive stress of 20 MPa is applied on the left boundary. The left boundary is drained by prescribing zero pore pressure, whereas all other boundaries are impermeable. The domain is discretized using 4050 bilinear quadrilateral elements, corresponding to 45 elements in the horizontal direction and 90 elements in the vertical direction. The fracture contact response is modeled using penalty formulation. The XFEM-based hydromechanical formulation is compared with the reference results of Damirchi et al. (2022), obtained using the Unified Embedded Finite Element Method (UEFEM). The comparison focuses on the pore-pressure evolution at monitoring Point A. As shown in Figure S4, the XFEM results obtained closely match the UEFEM solution.

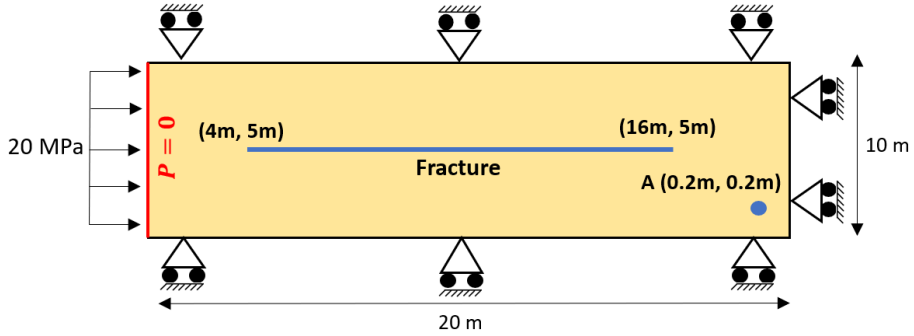


Figure S3. Schematic representation of the geometry and boundary conditions for the fractured consolidation benchmark, showing hydromechanical interactions between the porous medium and a centrally located horizontal discontinuity.

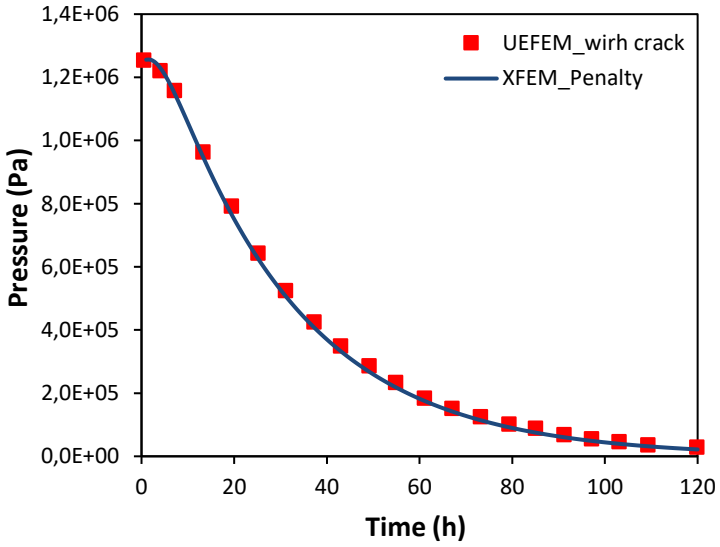


Figure S4. Comparison of pore-pressure evolution at monitoring Point A between the developed fully coupled XFEM model and the UEFEM results reported by Damirchi et al. (2022).

S3. Benchmark verification against SEAS BP3-QD

The numerical framework was further verified using the SCEC/USGS SEAS BP3-QD benchmark of Erickson et al. (2020), which considers a 2D plane-strain elastic medium containing a vertical rate-and-state fault. The benchmark adopts an aging-law formulation and a quasi-dynamic approximation in which radiation damping is used to represent inertial effects. The model parameters follow the official benchmark specification, including a 25 m element size, an initial effective normal stress of 50 MPa, a reference friction coefficient of 0.6, $a = 0.01 - 0.025$, $b = 0.015$, critical slip distance = 0.008 m, and a plate loading rate of 10^{-9} m/s.

Following the SEAS protocol, the response was classified as aseismic when the maximum fault slip rate was below 10^{-3} m/s and seismic when it exceeded this threshold. Output intervals of 0.1 years were used during aseismic periods, while a finer interval of 0.1 s was used during rapid slip events. The results were compared with the SEAS reference solution for the dx=25m and dip=90° case at the on-fault station located 10 km down-dip. Time histories of slip, slip rate, shear stress, and state variable were extracted for direct comparison. As shown in Figure S5, the present results reproduce the timing and magnitude of the aseismic and seismic slip episodes well. The slip rate, shear stress change, cumulative slip, and state variable evolution show close agreement with the reference solution, with only minor differences attributed to discretization and time-integration choices.

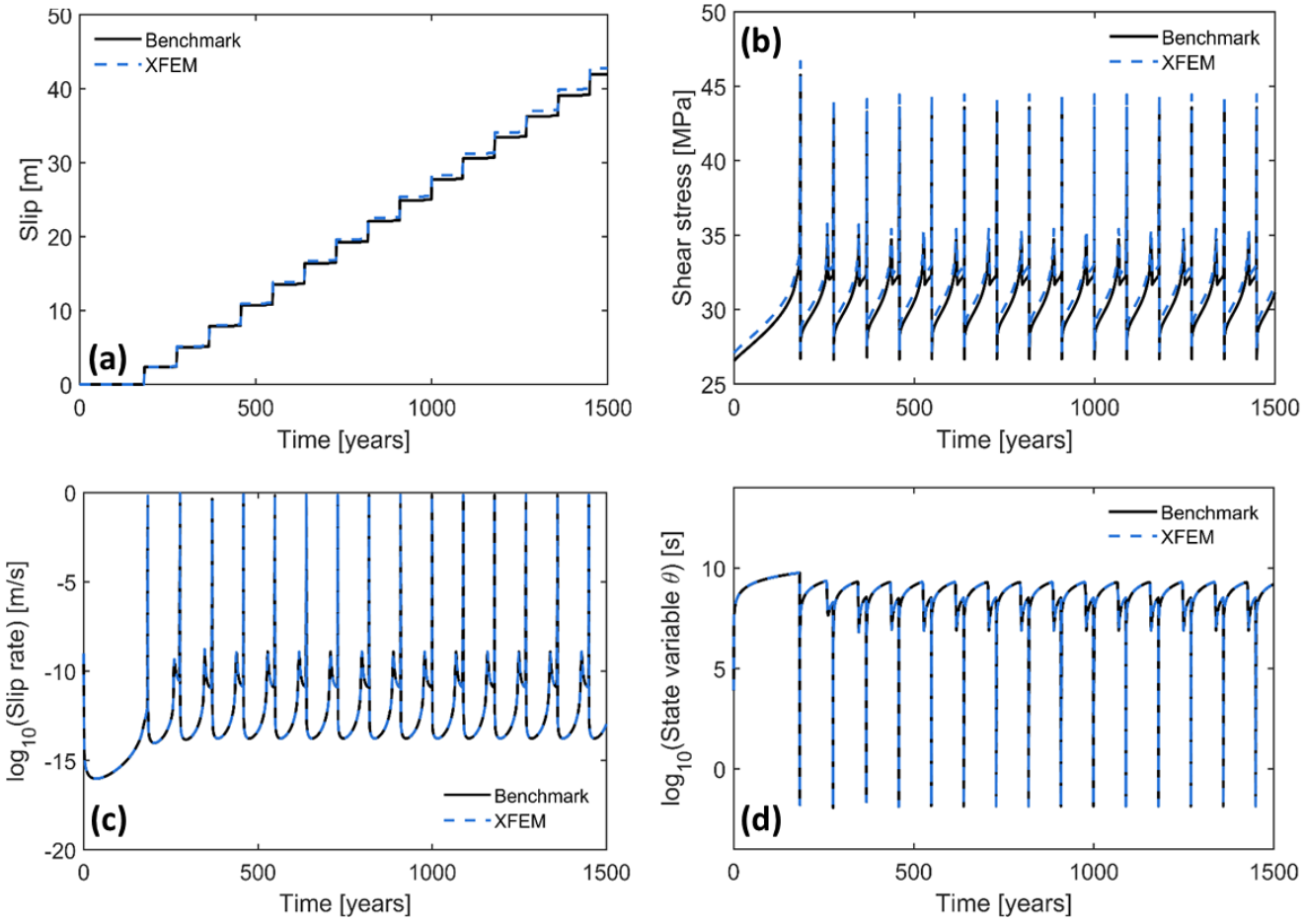


Figure S5. Comparison between the present XFEM-based results and the SEAS BP3-QD benchmark solution at the on-fault station located 10 km down-dip, showing the temporal evolution of (a) cumulative slip, (b) shear stress, (c) slip rate, and (d) state variable.

S4. Verification of central-difference explicit solution approach

The TPV205-2D dynamic rupture benchmark from the SCEC/USGS Earthquake Code Verification Exercise is used to evaluate the performance of the central-difference explicit component of the proposed hybrid solution approach. The model consists of a 60 km × 40 km homogeneous, linear-elastic domain containing a horizontal fault centered at (30 km, 20 km). The fault extends from x = 5 km to $x = 55$ km, giving a total length of 50 km. The elastic properties are defined by a compressional-wave velocity $V_p = 6$ km/s, shear-wave velocity $V_s = 3.46$ km/s, and density $\rho = 2670$ kg/m³. Rupture is permitted only within the central fault segment 15 km ≤ x ≤ 45 km; outside this region, slip is suppressed by assigning a very large static friction coefficient.

Within the slipping region, linear slip-weakening friction is used with static and dynamic friction coefficients $f_s = 0.67$ and $f_d = 0.52$, respectively, and a critical slip-weakening distance $D_c = 0.4$ m. The initial normal stress is $P_N = 120$ MPa, while the background initial shear stress is $P_t = 70$ MPa. To impose heterogeneous rupture conditions, three local shear-stress patches are introduced: $L_0 = \{28.5 \leq x \leq 31.5\ km\}$, $L_1 = \{21 \leq x \leq 24\ km\}$, and $L_2 = \{36 \leq x \leq 39\ km\}$. The shear stress is set to 81.6 MPa in L_0, 78 MPa in L_1, and 62 MPa in L_2. Since the shear stress in L_0 exceeds the static fault strength, this region acts as the rupture nucleation zone. Simulations are performed using element sizes of $\Delta x = 100$ m, penalty parameters $k_N = k_T = 10^7$ (Liu and Borja, 2013), a time step $\Delta x = 0.001$ s, and a total simulation time of 12 s. For verification, slip-rate and shear stress histories are evaluated at $x = 30$ km along the fault and compared against the SCEC/USGS reference results submitted by Brad Aagaar (aagaard.2; PyLith v1.7.0a - Tri3 100m) (Harris et al., 2009). The reference solution was generated using a split-node formulation with a characteristic element size of 100 m. The results obtained with our XFEM-based explicit dynamic solver show good agreement with the reference results reported by Aagaard (Fig. S6).

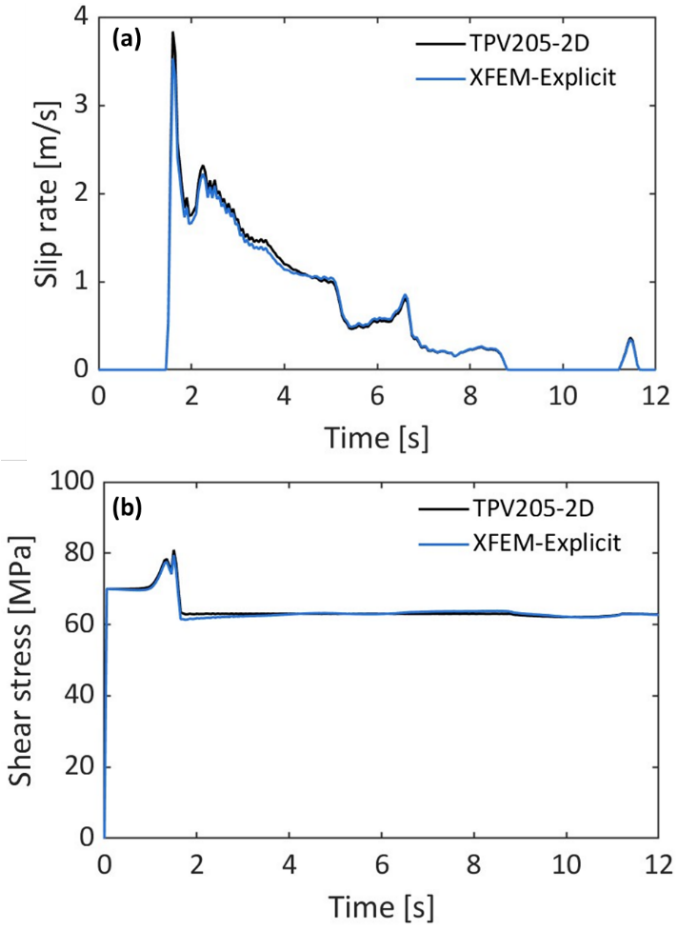


Figure S6: Comparison of the TPV205-2D benchmark response with the XFEM-based explicit dynamic solver: (a) slip-rate and (b) shear-stress time histories at $x = 30$ km.

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