Fluid-induced aseismic slip may explain the non-self-similar source scaling of the induced earthquake sequence near the Dallas-Fort Worth Airport, Texas

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Abstract

Numerous studies have reported the occurrence of aseismic slips or slow slip events along faults induced by fluid injection. However, the underlying physical mechanism and its impact on induced seismicity remain unclear. In this study, we develop a numerical model that incorporates rate-and-state friction fault and fluid injection to simulate the coupled processes of pore pressure diffusion, aseismic slip, and dynamic rupture. We establish a field-scale model to emulate the induced seismicity near the Dallas-Fort Worth Airport, Texas, where events with lower stress drops have been observed. Our numerical calculations reveal that the diffusion of fluid pressure induces aseismic slips and advances or delays seismic ruptures. Furthermore, the stress drops associated with aseismic slips indicate lower values (< 1 MPa), which may explain the observed variation in stress drops near the Airport. Simulations encompassing diverse injection operations and fault frictional parameters show that the interplay between the amount of pore pressure perturbations and stress states during the interseismic period influences the initiation, quantity, recurrence intervals, and source parameters of aseismic slips. However, the scaling relationship of moment (M0) with ruptured domain (r0) for all simulated events follows an unusual trend, M0[?]r04.3, similar to M0[?]r04.7 observed in the Airport sequence. Based on the consistent scaling, we hypothesize that the lower stress drop events in the Airport may be less dynamic ruptures, similar to aseismic slips as illustrated in our simulations.

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Key Points:

- Interaction between pore pressure changes and initial stress states induce aseismic slips that either advance or delay seismic ruptures
- Aseismic slips denote smaller stress drops (< 1 MPa) and lead to non-self-similar scaling characteristics
- Simulated events show diverse slip modes ranging from slow slip to seismic rupture and a similar scaling as observed in the Airport sequence
Abstract

Numerous studies have reported the occurrence of aseismic slips or slow slip events along faults induced by fluid injection. However, the underlying physical mechanism and its impact on induced seismicity remain unclear. In this study, we develop a numerical model that incorporates rate-and-state friction fault and fluid injection to simulate the coupled processes of pore pressure diffusion, aseismic slip, and dynamic rupture. We establish a field-scale model to emulate the induced seismicity near the Dallas-Fort Worth Airport, Texas, where events with lower stress drops have been observed. Our numerical calculations reveal that the diffusion of fluid pressure induces aseismic slips and advances or delays seismic ruptures. Furthermore, the stress drops associated with aseismic slips indicate lower values (< 1 MPa), which may explain the observed variation in stress drops near the Airport. Simulations encompassing diverse injection operations and fault frictional parameters show that the interplay between the amount of pore pressure perturbations and stress states during the interseismic period influences the initiation, quantity, recurrence intervals, and source parameters of aseismic slips. However, the scaling relationship of moment ($M_0$) with ruptured domain ($r_0$) for all simulated events follows an unusual trend, $M_0 \propto r_0^{3.3}$, similar to $M_0 \propto r_0^{4.7}$ observed in the Airport sequence. Based on the consistent scaling, we hypothesize that the lower stress drop events in the Airport may be less dynamic ruptures, similar to aseismic slips as illustrated in our simulations.

Plain Language Summary

Injection-induced earthquakes have presented significant obstacles to developing energy resources related to fluid injection, such as enhanced geothermal systems and shale gas development. However, the causes and impact of these earthquakes are not fully understood. Aseismic slip, which has slower velocities and longer durations than typical earthquakes, has been observed in induced earthquake studies. In this study, we use a numerical model to investigate how fluid pressures influence the slip properties of induced seismicity near the Dallas-Fort Worth Airport, Texas. Our model shows that elevated fluid pressure induces aseismic slip and advances or delays the fast slip (i.e., earthquakes). Throughout the multiple simulations, the interplay between pore pressure perturbations and stress conditions during the interseismic period emerges as the key factor in controlling the occurrence of aseismic slip. The aseismic slips show somewhat different stress release processes compared to globally observed natural earthquakes but exhibit similarities to observations in the Airport area. Therefore, we infer that the Airport events may exhibit less dynamic characteristics akin to the slow slip events generated in our modeling.

1. Introduction

Fluid injection into the subsurface is an important industrial practice used for developing geo-energy resources such as enhanced geothermal systems, CO$_2$ sequestration, and shale gas extraction worldwide (National Research Council, 2013). However, these fluid injections often induce seismicity, leading to the suspension and the economic loss of several projects (e.g., Pohang in Korea, Basel in Switzerland, the 2011 Preese Hall in UK) (Häring et al., 2008; Foulger et al., 2018; Lee et al., 2019). Assessment and mitigation of the seismic hazard from
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Injection-induced earthquakes are essential for sustainable energy development. To do this, it is key to understand the triggering mechanisms and source properties of induced earthquakes.

Injection-induced earthquakes can be triggered by two mechanisms associated with fluid injection: (1) elevated pore pressure that diffuses through rock pores and directly reduces effective normal stress (frictional resistance to slip) on pre-existing faults, and (2) poroelastic coupling, which is an elastic deformation of a porous medium that indirectly alters fault-loading conditions without hydraulic connection (Ellsworth, 2013). However, the triggering mechanisms associated with pore pressure changes alone remain controversial in explaining why geodetic observations have often detected aseismic slips associated with fluid injection (e.g., Éyre et al., 2022; Jiang et al., 2022; Pepin et al., 2022; Staniewicz et al., 2020), which require further interpretation of fault dynamics.

In addition to geodetic observations, a field-scale experiment in southeastern France has recorded aseismic slips using specially designed strainmeters, indicating that pore pressure increases resulting from fluid injection initially triggered aseismic slip on pre-existing faults (Cappa et al., 2019; Guglielmi et al., 2015). The source characteristics of the microseismicity (−3.9 < \( M_w \) < −3.1) in this experiment show low stress drops (≈0.01 MPa on average), which may suggest the occurrence of slow earthquakes influenced by the aseismic response and fluid pressure increases (Huang et al., 2019). Several seismological observations have also reported events with lower stress drops (Chen & Abercrombie, 2020; Goertz-Allman et al., 2011; Jeong et al., 2022; Yu et al., 2021). These lower stress drop events are mainly found at the beginning of the sequence and in proximity to injection wells, which gives rise to a non-self-similar scaling of induced earthquakes. For instance, Jeong et al. (2022) observed a magnitude dependence and distance trend in stress drops of the earthquake sequence at Dallas-Fort Worth (DFW) Airport, Texas (Figure 1). The low stress drops may indicate a dynamic weakening of the fault, which may be influenced by an increase in pore pressure and a reduction in effective normal stress (Goertz-Allman et al., 2011). The decrease in effective normal stress leads to a lower degree of interface locking on the fault and limits the magnitude of stress drops (Moreno et al., 2010). This may imply the presence of mixed modes between aseismic slip and seismic ruptures on the pre-existing fault in response to fluid injection.

In a tectonic environment, aseismic slip often occurs in combination with pore pressure diffusion, contributing to the moment budget and release of the strain accumulated on the fault (Durand et al., 2022; Ruhl et al., 2016). Studies in subduction zones suggest that aseismic creep can initiate or trigger large seismic ruptures and may be considered a precursor event for forecasting large earthquakes (Harris, 2017; Obara & Kato, 2016). Thus, aseismic slip plays a crucial role in altering the timing of earthquake occurrence, subsequent seismic cycles, and earthquake hazard assessment (Bürgmann, 2018; Lui et al., 2021). These findings highlight the importance of coupled modeling of dynamic ruptures and fluid pressure evolution to better understand the role of aseismic slip and the complex processes involved in injection-induced seismicity.

This study aims to investigate the influence of aseismic slip on the dynamic faulting process of induced seismicity by simulating the spatiotemporal evolution of pore pressure on a field-sized fault. To account for both aseismic and seismic fault slip behavior, we employ the spectral boundary integral method with a rate-and-state friction fault and pore pressure diffusion model under stable tectonic loading. We use the DFW Airport seismic sequence as a field example to set up a realistic model by matching bottomhole pressure, source parameters, and the
spatiotemporal distribution of DFW seismicity estimated by previous studies. We simulate the model both with and without fluid injections to obtain a physics-based understanding and forecast of earthquake processes. Subsequently, we extend the simulations by varying injection operation inputs and fault frictional parameters to gain insights into the involved physical mechanisms and their impact on induced seismicity, ultimately facilitating the development of strategies for mitigating seismic hazards.

2. Models and Methods

2.1. Induced Seismicity in the DFW

DFW Airport was previously considered an area of low tectonic deformation over the past 300 Ma (Magnani et al., 2017). However, induced seismicity began to occur with the development of unconventional oil and gas production since 2008 (Frohlich et al., 2011; Ogwari et al., 2018). The initial sequence starting in October 2008 involved 10 events (2.6 < M < 3.0) observed by the regional seismic network. Subsequently, a local seismic network installed by Southern Methodist University recorded 11 swarm-like earthquakes with high sampling data (200 samples per second) between November 20 and December 2, 2008 (DeShon et al., 2019). The majority of the earthquakes (9 out of 11 events) occurred within a span of 3 hours on November 20, 2008, while the others were detected on November 28 and December 1 of the same year. Although the fault length in the DFW Airport area exceeds 50 km (Hennings et al., 2019; Horne et al., 2020), these events occurred in the vicinity of the nearest injection well (API 42-439-32673) and traced a ~1 km linear feature that was parallel to a pre-existing fault (Figure 1a). Jeong et al. (2022) estimated lower stress drops for the 11 Airport earthquakes and abnormal source scaling, with stress drops increasing with moment magnitude and radial distance from the injection point within the first 1.5 km (Figures 1b, c). The Airport fault is optimally oriented in the direction of the regional stress field, meaning that small stress perturbations can potentially nucleate earthquakes along the faults (Hennings et al., 2019; Horne et al., 2020). Fluid injection began at the nearest well in September 2008, prior to the earthquakes, and was subsequently shut down in August 2009, resulting in about a year of injection. Ogwari et al. (2018) demonstrated that seismicity continued to migrate mainly towards the northeast, parallel to the pore pressure diffusion front. The earthquake depths are ~4.5 km below sea level (Frohlich et al., 2011), while the injection depth interval of interest is shallower, ranging from 3.1 to 4.2 km.
Figure 1. Seismic characteristics of the Dallas-Fort Worth (DFW) Airport area, illustrated by (a) a map of the seismicity, stress drop estimates increasing with (b) moment magnitude $M_W$ and (c) distances from the nearest injection well. In (a), black lines and black dots represent the faults and the downthrown hanging-wall block, respectively, from Horne et al. (2020). The seismogenic fault is highlighted as the bold line. The inverted triangle indicates the location of the injection well. In (b, c), the error bars represent the 95% confidence limits. The figures are modified from Jeong et al. (2022).

2.2. Rate-and-State Friction Fault

We simulate dynamic earthquake sequences using the spectral boundary integral equation method, which resolves both aseismic and seismic slips on faults (Lapusta et al., 2000). Our model implements the long-term evolution of slip and stress along the fault, taking into account inertial effects during rapid seismic events. Thus, the model results in a fully dynamic process, in which the stress is redefined from the final stress of the previous event after an earthquake rupture. Friction on the fault is controlled by the laboratory-derived rate-and-state friction law, which represents the evolution of friction depending on slip velocity and frictional state (Dieterich, 1979; Marone, 1998; Ruina, 1983). The fault slip is governed by the fault strength $\tau_f$ given by

$$ \tau_f = (\sigma_n - p) \left[ f_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{d_c} \right) \right] $$

where $\sigma_n$ is the normal stress, $p$ is the pore pressure, $f_0$ is a reference friction coefficient, $V$ is slip velocity, $V_0$ is the reference velocity, $\theta$ is the state variable representing the loss of asperity contacts, and $d_c$ is the critical slip distance for state evolution. Note that $(\sigma_n - p)$ is the effective normal stress. Parameters $a$ and $b$ are the frictional stability factors for the direct effect of changes in slip velocity and the evolutionary effect of the state variable, respectively. We use the aging law to estimate the evolution of $\theta$ (Dieterich, 1979) as

$$ \frac{\partial \theta}{\partial t} = 1 - \frac{V \theta}{d_c}.$$  

At steady state, $\theta = d_c/V$, the fault strength $\tau_s$ is rewritten as
\[ \tau_s = (\sigma_n - p) \left[ f_0 + (a - b) \ln \left( \frac{V}{V_0} \right) \right]. \] (3)

The velocity strengthening (VS) is the creeping region defined by \((a - b) > 0\), and the velocity weakening (VW) patch is the locked asperity presented by \((a - b) < 0\), which promotes earthquake nucleation and rupture propagation. The rate-and-state friction properties \((a, b, \text{and } d_c)\) are assumed to be constant and independent of pore-pressure perturbations.

Dynamic rupture nucleates when the slipping region on the VW patch exceeds the nucleation size \(h^*\) suggested by Rubin & Ampuero (2005) as

\[ h^* = \frac{2}{\pi} \frac{\mu^* b d_c}{(b-a)^2(\sigma-p)} \] (4)

where \(\mu^* = \mu\) for mode III ruptures and \(\mu^* = \mu/(1-\nu)\) for mode II ruptures, where \(\mu\) is the shear modulus and \(\nu\) is the Poisson’s ratio.

We set up a 1D planar fault with a length of 1,000 m \((L_x)\) based on observed seismicity (Figure 1a). This fault is embedded in a homogeneous 2D medium, and thus we resolve a 2D antiplane shear problem (Figure 2). We assume the presence of a hydraulic pathway between the injection wellbore and the fault surface, and thus fluid is directly injected into the fault. The VW patch is located in the center of the fault and surrounded by VS regions under tectonic loading \((V_{pl})\). The diameter of the VW patch \((d)\) is set to 200 m, determined from the average rupture radius of 100 m estimated by Jeong et al. (2022). The shear wave velocity \((C_s)\) and shear modulus at the fault depth are based on previous studies of seismicity in north Texas (Quinones et al., 2018; Quinones et al., 2019). We simulate the earthquake cycle for 15 years with an adaptive time step, which results in a short time step during seismic periods relative to interseismic slip (Lapusta et al., 2000; Lapusta & Liu, 2009). The threshold of seismic rate is set to 0.01 m/s, following Chen & Lapusta (2009), while the aseismic slip is empirically defined by a threshold of \(1.46 \times 10^{-9}\) m/s, twice the value of \(V_{pl}\) (Figure 3). The detailed fault parameters are documented in Table 1.
Figure 2. Schematic illustration of the fault framework. The figure on the right-hand side displays the fault layout, which consists of a 1 km long fault with a 200 m diameter velocity-weakening (VW) asperity at the center (red) and two 300 m velocity-strengthening (VS) regions on both sides (black). The edges of the fault are loaded by a slow tectonic slip rate ($V_{pt}$) of 23 mm per year (green). Fluid is injected at a location -200 m from the center of the fault within the left-hand side VS region.

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear wave speed</td>
<td>$C_s$</td>
<td>3,460 m/s</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>$\mu$</td>
<td>32 GPa</td>
</tr>
<tr>
<td>Loading slip rate</td>
<td>$V_{pt}$</td>
<td>23 mm/year</td>
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<tr>
<td>Reference slip velocity</td>
<td>$V_0$</td>
<td>$10^{-6}$ m/s</td>
</tr>
<tr>
<td>Reference friction coefficient</td>
<td>$f_0$</td>
<td>0.6</td>
</tr>
<tr>
<td>Characteristic slip distance</td>
<td>$d_c$</td>
<td>160 $\mu$m</td>
</tr>
<tr>
<td>Effective normal stress</td>
<td>$(\sigma_n - p)$</td>
<td>50 MPa</td>
</tr>
<tr>
<td>Fault length</td>
<td>$L_x$</td>
<td>1,000 m</td>
</tr>
<tr>
<td>Patch diameters</td>
<td>$d$</td>
<td>200 m</td>
</tr>
<tr>
<td>Nucleation size</td>
<td>$h^*$</td>
<td>78 m</td>
</tr>
<tr>
<td>Rate-and-state properties in VW region</td>
<td>$a, b$</td>
<td>0.015, 0.019</td>
</tr>
<tr>
<td>Rate-and-state properties in VS region</td>
<td>$a, b$</td>
<td>0.015, 0.011</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>$\Delta x$</td>
<td>0.28 m</td>
</tr>
</tbody>
</table>
To simulate induced seismicity, we integrate pore pressure diffusion into the rate-and-state fault model. The 1D fluid transport equation is given by
\[
\frac{\partial p}{\partial t} = \frac{\partial}{\partial x} \left[ D \frac{\partial p}{\partial x} \right] + G
\] (5)
where \( p \) is pore pressure, \( D \) is hydraulic diffusivity, and \( G \) represents the potential source at the injection location and time. The hydraulic diffusivity is estimated using the equation
\[
D = \frac{k \rho g}{\eta S}
\]
where \( k \) is permeability, \( \rho \) is density, \( g \) is gravitational acceleration, \( \eta \) is viscosity, and \( S \) is specific storage. We take these parameters based on previous research conducted in Azle, Texas, which is assumed to have similar geomechanical characteristics to the DFW Airport area (Hornbach et al., 2015, see also Table 2). The potential source is determined from bottomhole pressure estimated from surface pressure using an in-house algorithm for the single injection well (Gao et al., 2021). For the single injection well near the Airport, the average rate of bottomhole pressure is 17.4 Pa/s, which is used as a constant fluid source. We assume that fluid is injected into the VS region, located 200 m away from the fault center (see Figure 2). For simplicity, we neglect changes in porosity and permeability. The detailed parameters of pore pressure diffusion are given in Table 2.

We solve the pore pressure changes using the explicit finite difference method. To ensure numerical stability, we use Von Neumann stability analysis, \( \frac{D\Delta t}{\Delta x^2} < \frac{1}{2} \) where \( \Delta t \) and \( \Delta x \) are time and spatial resolutions, respectively. After the injection begins, the time resolution follows that of fluid injection (\( \Delta t \)) until the simulation is completed. This accounts for the continued diffusion of the pore pressure front along the fault even after injection stops. Due to the short time resolution required for dynamic ruptures, the pore pressure perturbations are not processed during seismic ruptures. We omit the first event to avoid effects from initial conditions, and thus the fluid injection begins after the foremost seismic rupture. We also ignore poroelastic effects, which are relatively smaller than pore pressure perturbations (Zhai & Shirzaei, 2018).

<table>
<thead>
<tr>
<th>Parameter description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid injection rate</td>
<td>( G )</td>
<td>17.4 Pa/s</td>
</tr>
<tr>
<td>Permeability</td>
<td>( k )</td>
<td>( 1.0 \times 10^{-15} ) m²</td>
</tr>
<tr>
<td>Fluid density</td>
<td>( \rho )</td>
<td>( 1.031 ) kg/m⁻³</td>
</tr>
<tr>
<td>Gravitational acceleration constant</td>
<td>( g )</td>
<td>( 9.81 ) m/s</td>
</tr>
<tr>
<td>Fluid viscosity</td>
<td>( \eta )</td>
<td>( 1.1 \times 10^{-3} ) Pa·s</td>
</tr>
<tr>
<td>Specific storage</td>
<td>( S )</td>
<td>( 13 \times 10^{-6} ) m⁻¹</td>
</tr>
<tr>
<td>Hydraulic diffusivity</td>
<td>( D )</td>
<td>( 7.1 \times 10^{-4} ) m²/s</td>
</tr>
<tr>
<td>Time resolution for pore pressure model</td>
<td>( \Delta t )</td>
<td>( 55.6 ) s</td>
</tr>
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</table>

3. Results

3.1. Aseismic Slips

We simulate the earthquake cycle and estimate the maximum slip velocity (\( V_{max} \)) over time using the rate-and-state friction fault model, considering both scenarios with and without fluid injection (Figure 3). Here, the earthquake cycle without fluid injection serves as a reference.
Our simulations demonstrate consistent recurrence intervals of \( \sim 1.75 \) years in the reference model. When fluid is injected at 8.47 years, which corresponds to 50\% of the recurrence interval after the first earthquake, we observe that the pore pressure perturbation associated with fluid injection leads to advanced timing of seismic activities compared to the reference scenario. The recurrence times from the pore pressure perturbation scenario show some variation but gradually converge toward the event timings observed in the reference scenario after the suspension of fluid injection. This suggests that fluid-driven stress perturbations gradually weaken after injection stops, and the stress states surrounding the fault recover to tectonic conditions over time.

Shortly after the injection begins, we observe two slow slip events before the seismic rupture, characterized by relatively smaller velocities and longer durations compared to those of the seismic ruptures (Figure 3b). Additionally, after injection stops, one more slow slip event is observed just before the third seismic rupture in the fluid-simulation (Figure 3c). The slip rate of these aseismic slips appears to increase over the simulation time. In this study, we refer to these slow slip events as aseismic slips.

**Figure 3.** Maximum slip velocities \( (V_{max}) \) plotted against simulation time for a fault length of 1,000 m with a 200 m diameter VW asperity. Two scenarios are simulated: one without fluid injection (red) and one with fluid injection (blue). (a) displays the maximum velocity range over 7 to 15 years. Note that no seismic events are triggered before 7 years. The gray-shaded area highlights the time range for fluid injection, spanning from 8.47 to 9.47 years. (b) zooms in on the injection period including the first and second aseismic slips and (c) zooms in on the period including the third aseismic slip depicted in (a). The horizontal dashed lines denote the threshold slip velocities that define seismic slip \( (10^{-2} \text{ m/s}) \) and aseismic slip \( (1.46 \times 10^{-9} \text{ m/s}) \).

To investigate the aseismic slips observed in Figure 3, we analyze changes in pore pressure, slip rate, and shear stress (Figure 4). In our reference simulation, which only implies tectonic loading, earthquakes rupture the entire VW asperity, and there is little variation during the interseismic period on the fault (Figure 4a). In contrast, when fluid is injected onto the fault, aseismic slips partially release the cumulative stress prior to seismic rupture, with rupture areas that are smaller than those of the subsequent seismic rupture (Figures 4b, c). These aseismic slips mainly occur on the left-hand side of the asperity, close to the injection point.
Figure 4. Pore pressure diffusion (top), logarithmic slip rate (middle), and logarithmic shear stress (bottom) on the fault with simulation time steps for two scenarios: (a) no-injection and (b, c) fluid injection at -200 m from the center of the VW asperity, as illustrated by black vertical lines. In (b, c), white arrows indicate the aseismic slips associated with pore pressure diffusion. The title specifies the range of simulation time in years.

Figure 5 illustrates the distribution of cumulative slip and stress drop (the difference in the shear stresses before and after events) along the fault for the seismic rupture that occurred during the injection period. Here, the rupture domain $\Sigma$ represents the region with a net positive slip and is defined as $\Sigma_{\text{seis}} = \{ x \in L_x | \delta(x) > 0 \}$ for seismic events (Figure 5a). The ruptured area includes both VS and VW regions. However, within the VW asperity, positive stress drops are exclusively observed, whereas negative stress drops are distributed throughout the VS regions (Figure 5b).
Figure 5. Distribution of (a) cumulative slip and (b) stress drop as a function of position along the fault for the seismic rupture that occurred during the injection period with the fluid injection scenario. The gray-shaded area denotes the VW asperity. Note that the ruptured domain is defined as the region where slip is non-zero in (a).

In the case of the aseismic slips, non-zero slips are observed both within and outside the VW patch (Figures 6a, b, c), indicating a complex rupture area. To determine $\Sigma$ for aseismic slips, we approximate the ruptured domain as the locations where the slip rate exceeds $1.46 \times 10^{-9}$ m/s during the events, defined as $\Sigma_{aseis} = \{ x \in L_x | \mathcal{V}(x) > 1.46 \times 10^{-9} \text{ m/s} \}$, following the methodology by Perry et al. (2020) (see also Figures 6d, e, f). The ruptured domains are mainly situated on the left side of the VW asperity, near the injection location, suggesting that aseismic slip is likely induced by stress perturbations associated with pore pressure diffusion and reduced effective normal stress on the fault. The stress drop distribution of the aseismic slips reveals that the shear stress is partially changed within a limited rupture area, in contrast to the seismic rupture that occurs within the entire VW region (Figures 5b, 6g, h, i).
Figure 6. Distribution of (a-c) cumulative slip, (d-f) all slip rates during aseismic events, and (g-i) stress drop along the fault for the aseismic slips in three columns: the first (left), the second (middle), and the third aseismic slips (right). In (d-f), the rupture dimension is defined as the area above the horizontal line, which corresponds to the threshold of aseismic slips ($1.46 \times 10^{-9}$ m/s). The VW asperity is highlighted as the gray-shaded area in (a-c, g-i) and indicated by vertical lines in (d-f).

3.2. Lower Stress Drops of Aseismic Slips
We estimate source parameters for the simulated events. After calculating rupture areas using the defined criteria above, we estimate an average stress drop based on energy considerations $\Delta\sigma_E$ (Noda et al., 2013) as

$$
\Delta\sigma_E = \frac{\int \Delta\sigma(x)\delta_f(x)d\Sigma}{\int \delta_f(x)d\Sigma}
$$

(6)

where $\Delta\sigma(x)$ is the stress drop distribution and $\delta_f(x)$ is the final slip distribution, which is used as the weighting function. The effective source radius ($r_0$) is determined based on the estimated ruptured domain as $r_0 = \sqrt{\Sigma^2/\pi}$ (Schaal & Lapusta., 2019) for a circular crack model (Eshelby, 1957). The moment is estimated as

$$
M_0 = \frac{16}{7} \Delta\sigma_E r_0^3
$$

(7)

Figure 7 depicts the variation of seismic moments and average stress drops. The seismic ruptures exhibit larger moments and stress drops compared to aseismic slips. The source parameters of seismic ruptures are consistent with each other and remain independent of time, distance from the injection well, and pore pressure changes. Here, the average pore pressure values are calculated using the same method employed for calculating stress drop, replacing stress drop distribution with pore-pressure distribution in equation 6. In the case of the three aseismic transients, we observe temporal increases in both moments and stress drops, similar to the findings of maximum slip velocity (Figures 3b, c). The larger stress drops observed for the later aseismic slip events can be explained by equation 4, which suggests that the nucleation size can increase due to the decrease in effective normal stress caused by enhanced pore pressure. A significant perturbation may contribute to the growth of nucleation size and result in a larger rupture radius. The estimated pore pressure values are 0.07, 0.18, and 0.58 MPa for the first, second, and third aseismic slips, respectively, providing support for the hypothesis of nucleation growth (Figure 7d). Moreover, the stress drops of aseismic slips show a positive trend with the distance from the injector. Here, the distance from the injection point is estimated as the separation between the injection location and the maximum slip rate on the ruptured area (Figures 6d, e, f). Consequently, stress drops increase with both the moments and the radial distance from the injection well through numerical modeling, which is consistent with the observations in the DFW Airport sequence (Figures 1b, c). Therefore, aseismic slips may be the main cause of the moment dependent trend and the distance dependence in stress drop scaling.
3.3. Effects of Injection Operation Parameters

We perform multiple simulations with different fluid injection inputs to investigate how injection parameters influence the earthquake characteristics (Figure 8). Here, the original model with fluid injection is used as a reference.
First, we compare the effects of various injection locations at -100, -200, and -300 m from the fault center (Figures 8a, b). Note that the negative sign denotes the left-hand side of the VW patch (Figure 2). Both aseismic slips and seismic ruptures occur earlier than the reference at the closer distance of -100 m (directly injected into the left tip of the VW area), while the events are delayed at a longer separation of -300 m. The recurrence times of the -100 m and -200 m cases are similar, but the recurrence intervals of the -300 m distant injection show a longer duration than the others. However, the difference in recurrence time among the three cases gradually diminishes at the end of the simulation, as shown in Figure 8a. The maximum velocity of aseismic slips also follows the same pattern as the reference model shown in Figure 3, where the first aseismic slip has a lower amplitude than the second (Figure 8b). For the 300 m separation case, only one aseismic slip is found, suggesting that the separation also controls the number of aseismic slips.

Next, we modulate the injection volume that is twice larger than the reference model (Figures 8c, d). The maximum velocities show that higher fluid pressure leads to faster occurrences of aseismic slips and seismic ruptures. After the injection stops, the scenario of a larger injection volume shows initially short recurrence intervals and subsequently longer recurrence intervals. During the injection period, the maximum slip velocities of two aseismic slips exhibit higher amplitudes than those in the reference model. However, after the injection ends, no additional aseismic slips occur, which differs from the reference model.

We investigate different injection durations of 3, 6, and 12 months (Figures 8e, f). A short injection duration of 3 months leads to a delay in seismic triggering associated with a small aseismic slip. Note that the $V_{max}$ of aseismic slip resulting from the 3-month injection model is lower than the aseismic criteria specified in this study, thus we exclude this event from the analysis. Seismicity triggered by the 6-month duration does not differ significantly from the reference (12-month period) during the injection phase, but the occurrence time of a third aseismic slip is more delayed, which is at ~10.64 years. Both the 3-month and 6-month injection scenarios exhibit longer recurrence intervals compared to the reference. However, toward the end of the simulation, the recurrence times of both shorter duration models gradually converge to the reference.

Lastly, fluid is injected into our model at various times during a seismic cycle (Figures 8g, h). When fluid is injected earlier (7.94 years, 20% of the recurrence interval) compared to the reference (8.47 years, 50% of the recurrence interval), the occurrence of both aseismic slips and seismic ruptures is accelerated. The seismic rupture occurs at ~8.77 years, which is a delay of ~0.83 years from the initiation of injection. Since the reference model exhibits a ~0.51 year offset between injection initiation and earthquake occurrence, we infer that earlier injection can lead to relatively delayed seismic events. The aseismic slips have a smaller $V_{max}$ than the reference, but there are a total of three events, one more than the reference during the injection period. Note that no additional aseismic event occurs after the injection is stopped. When fluid is injected at 8.99 years (80% of the recurrence interval), an aseismic slip and an earthquake occur shortly after the injection (Figure 8h). The delay time between injection initiation and seismic rupture is ~0.2 years. These results can be explained by the cumulative stress state on the fault. Injection onset close to the coseismic period quickly triggers earthquakes, while fluid injection starting in the middle of the interseismic period relatively delays the seismic rupture. The three different injection timings result in similar recurrence intervals in subsequent earthquake cycles,
suggesting that the start times of injection have minimal impact on changes in the recurrence intervals compared to other injection operation parameters.

**Figure 8.** Maximum slip velocities over time for various injection scenarios. The left-hand column represents the long term time period, while the right-hand column provides a zoomed-in view of the injection period. The different injection scenarios include: (a, b) injection at different locations: -100 m in red, -200 m in blue, and -300 m in orange; (c, d) different injection volumes: twice the amount of injection volume (34.8 Pa/s) in green compared to the reference volume (17.4 Pa/s) in blue and zero volume in red; (e, f) different injection durations: 3, 6, and 12
months displayed by orange, purple, and blue lines; (g, h) different injection onset times: 7.94, 8.47, and 8.99 years, represented by red, blue, and orange. The colored horizontal lines in (e, f) visually indicate the duration of 3 and 6 months. Inverted triangles in (g, h) denote the onsets of fluid injection, and the vertical dashed line in (h) represents a coseismic rupture from a no-fluid simulation. In all figures, the horizontal dashed lines denote the threshold slip velocities that define seismic slip ($10^{-2}$ m/s) and aseismic slip ($1.46 \times 10^{-9}$ m/s). The bold text in the legend corresponds to the reference model setup. Note that the time scale in (h) slightly differs from the other right-hand column plots due to the early injection scenario.

Figure 9 illustrates the source scaling of aseismic slips derived from a number of injection settings shown in Figure 8. Events that occurred in the early to middle of the interseismic period show lower stress drops (< 0.1 MPa) and moments, whereas events that occurred later in that period or closer to the seismic rupture time exhibit consistent source parameters estimated in the Airport sequence. In all simulations, the source scaling of aseismic slips is estimated to follow a relationship of $M_0 \propto r_0^{3.4}$. When considering the inclusion of seismic ruptures in the scaling analysis, the relationship becomes $M_0 \propto r_0^{4.3}$, which is similar to the Airport observations ($M_0 \propto r_0^{4.7}$). Thus, aseismic slips may be the main cause of non-self-similar scaling in induced seismicity. We acknowledge, however, that linear regression is estimated with a limited number of events with a small range of rupture radius and moments.

![Figure 9](image-url)  
*Figure 9.* Stress drops as a function of the seismic moment for aseismic slips resulting from various injection parameters shown in Figure 8. The simulations with different separations between injection locations and center of VW asperity, 100 m (red) and 300 m (orange), are represented by transparent triangles, while green inverted triangles and purple squares
correspond to a twice larger injection volume and shorter injection duration (6 months). Asterisks indicate the scenarios with early injection at 7.94 years (red) and late injection at 8.99 years (orange). The observed stress drops in the Airport earthquake sequence (Jeong et al., 2022) are denoted by green diamonds.

3.4. Effects of Fault Parameters

We conduct multiple simulations without fluid injection, varying fault frictional parameters (i.e., $a$, $b$, and $d_e$), to investigate the effects of fault friction on our model. To ensure reliable results, we eliminate simulations that exhibit the absence of seismic events within a simulation time of 15 years, irregular recurrence intervals, and the presence of aseismic slips during the interseismic period (Figure S1). After the tests, we identify the lowest frictional fault ($a - b = -0.0036$) and the highest frictional fault ($a - b = -0.0050$) with $d_e$ ranging from 40 to 220 μm. Based on these findings, we focus on three fault scenarios: the lowest frictional fault, the reference fault ($a - b = -0.0040$), and the highest frictional fault, combined with different values of $d_e$, for the purpose of this study. Next, we add fluid injection into these frictional simulations to induce aseismic transients. Simulations that do not exhibit any aseismic events by fluid injection are subsequently excluded from the analysis. Recognizing that the early injection scenarios can lead to an increased number of aseismic slips from the injection operation tests (Figure 8), we incorporate these earlier injection scenarios into the multiple fault parameter tests.

Figure 10 illustrates the source parameters estimated by simulations using various fault frictional parameters in the fluid-injection model. Our simulations produce a wide spectrum of slip modes (events with a wide range of slip rates). In particular, we identify three distinct types of events: (1) full seismic rupture, (2) partial seismic rupture, and (3) aseismic slips. In the case of a full seismic rupture, the entire VW region slipped, as depicted in Figure 5. On the other hand, partial ruptures are characterized by the rupture of only a portion of the VW asperity (see Figure S2). Consequently, the moment and rupture radius associated with partial ruptures are smaller than those of complete ruptures. A seismic moment of $10^{13}$ Nm and a rupture radius of 130 m can serve as straightforward criteria for distinguishing between partial and full ruptures (Figure S3). Despite their differences in extent, both full and partial seismic ruptures exhibit similar stress drop values (3.57 and 3.06 MPa for full and partial ruptures) and scaling properties. The stress drops observed in both types of ruptures appear to be independent of seismic moments, distance from the injector, and averaged pore pressure perturbation (Figures 10a, b, c).

The aseismic slips, which are the primary focus of this study, show different source properties from those of partial/full ruptures. For the lowest, reference, and highest frictional faults, the average stress drops are 0.11, 0.11, and 0.16 MPa, respectively. These values are a factor of 10 lower than the average stress drop of both seismic ruptures. Therefore, the aseismic slips can be separated from both ruptures based on the stress drop levels (Figure 10). Stress drops and moments of aseismic slips exhibit a wide distribution, with some overlapping with the Airport events (see also Figure S2). Moreover, the stress drops of the aseismic slips increase with the seismic moments. The source scalings are found as $M_0 \propto r_0^{3.54}$, $M_0 \propto r_0^{3.53}$, and $M_0 \propto r_0^{3.63}$ for the lowest, reference, and highest frictional faults, respectively. These source scaling relationships are consistent with the scaling estimated in various injection operation inputs.
$M_0 \propto r_0^{3.4}$, suggesting a similarity in the energy release patterns of the aseismic transients (Figure 10a). When both seismic ruptures are incorporated into aseismic slips, the scaling follows $M_0 \propto r_0^{4.3}$, closely resembling the scaling observed in the Airport sequence, $M_0 \propto r_0^{4.7}$.

The stress drop estimates of the aseismic slips show a slightly increased trend (slope = 0.42 on a log scale) with distance from the injection point (Figure 10b), which is smaller than the DFW observation (slope = 1.40). The stress drops also exhibit a positive correlation with pore pressure perturbation, with a slope of 0.57 on a log scale (Figure 10c). The pore pressure perturbations are higher than the stress drop estimates by an average of ~0.13 MPa (Figure 10d). In general, the occurrence of aseismic slips releases the stress accumulated during the interseismic period, potentially delaying seismic events (i.e., slip deficit). However, these external pressures may prevent the accumulation of slip deficit associated with aseismic transients, ultimately advancing the occurrence of seismic ruptures. Detailed results from all simulations can be found in Datasets in the supporting information (Dataset S1 for aseismic slips and Dataset S2 for seismic ruptures).
Figure 10. Source parameters of simulated events obtained from different injection inputs (asterisks) and fault frictional parameters (circles). (a-c) show the relationship between stress drops and (a) seismic moment, (b) distance from the injection point, and (c) average pore pressure changes. The lowest \(a - b = -0.0036\), reference \(a - b = -0.0040\), and highest frictional faults \(a - b = -0.0050\) are differentiated by different sizes and colors. In (a), the green diamonds represent the observed stress drops in the Airport earthquake sequence (Jeong et al., 2022). The horizontal dashed lines in (a-c) can distinguish aseismic slips from partial or full ruptures. In (d), a horizontal line represents the average value of the ratio between stress drop and pore pressure on a logarithmic scale.

4. Discussion

We conduct simulations of dynamic rupture on rate-and-state friction faults with spatially varying pore pressure perturbations to investigate the seismicity and source properties of injection-induced earthquakes. Our numerical modeling shows that injection-induced pore pressure perturbations trigger a continuous spectrum of slip behavior ranging from aseismic slip to seismic rupture, consistent with field and laboratory observational studies (Guglielmi et al., 2015; Yu et al., 2021). Aseismic slip/slow slip events occur prior to the dynamic ruptures and between the injection source and the seismogenic region (seismic source location), which alter the timing of subsequent seismic events. This supports the claims in earlier studies that injection-triggered aseismic slips contribute to the triggering of seismicity. Additionally, the onset times of aseismic slips, recurrence times of seismic ruptures, and the number of aseismic slips are controlled by various injection options and fault frictional parameters. However, the source scaling and stress release processes remain independent of injection operation inputs and fault parameters, suggesting there is a consistent scaling between simulations. Consequently, when considering the source properties of all simulated events, we observe a non-self-similar scaling, as observed in the Airport sequence.

The causal mechanism of aseismic slip may be attributed to the reduction of effective normal stress resulting from increases in pore pressure. Changes in fluid pressure are widely recognized to cause transitions between stable and unstable slip behavior on faults (Bürgmann, 2018). This can occur when reduced shear strength or slip resistance due to stress redistribution leads to slips in a part of the asperity while the rest of the asperity remains stronger. When faults are not fully locked during the interseismic period, stress perturbations associated with a fluid injection can cause the fault to release a portion of its energy (Ji et al., 2023). Numerical modeling by Marguin & Simpson (2023) suggest that fluid pressure perturbations result in slow slip events that have relatively lower stress drops, slip, and slip velocity. Another numerical modeling study by Lengliné et al. (2023) suggest that increased pore pressure may stabilize seismogenic patches and lead to a transition from seismic to aseismic behavior. Consequently, changes in effective normal stress can produce the non-self-similar source scaling observed in our modeling results.

We observe partial ruptures in scenarios with various fault frictional parameters (Figure 10). These partial ruptures show stress release in a part of the asperity, with similar source radius and moments as aseismic slips, but with larger stress drops, comparable to complete seismic ruptures. Furthermore, the stress drops are unaffected by moment and pore pressure perturbations,
in contrast to the source properties of the Airport sequence. Thus, these partial ruptures can be
distinguished from aseismic slips in our model and earthquakes occurring at the Airport area.
The slip behavior of an isolated asperity is determined by the ratio of nucleation length to patch
size (Rubin & Ampuero, 2005). Cattania & Segall (2019) suggest that a ratio greater than 6
between the asperity radius and nucleation radius leads to the occurrence of partial ruptures,
while Yin et al. (2023) propose a ratio of 16.24 between seismogenic width and nucleation
length as indicative of partial ruptures accompanied by fault interactions. In our model, the ratios
of VW and $h^*$ ranged from 0.94 to 6.44. The majority of partial ruptures occurred at smaller $d_c$
values (40-60 $\mu$m), with ratios ranging from 3.44 to 6.44 (refer to Dataset S2). Partial ruptures
are not observed in the reference simulations ($d_c=160$ $\mu$m). Hence, the occurrence of partial
ruptures may depend more on the size of nucleation length and numerical settings rather than
pore pressure increases.

Several studies have proposed heterogeneities on the fault as the causes of low stress drop
events observed in induced seismicity. Yu et al. (2021) suggest that slow slip events can occur
due to fractured rock volume associated with fluid injection and hydraulic fracturing. These
fractures can decrease pore pressure and increase effective normal stress, thereby inhibiting slip
acceleration. Pennington et al. (2022) suggest that low stress drop events observed in injection-
induced seismicity are derived from immature faults, and that the initial stress state and fault
strength are the primary controlling parameters for reactivated faults, rather than pore pressure
changes. For instance, the $M_w$ 4.0 Guthrie earthquake occurred in a strong VW area, while the
low-stress drop events of the first sequence occurred in a weak VW patch. Through numerical
simulations, Lin & Lapusta (2018) suggest that a complex fault shape with heterogeneous
strength may be the reason for stress drop variations, and thus, a simple rupture model can
overestimate the rupture area and underestimate the stress drops. In our study, based on findings
from diverse simulations, we suggest that the occurrence of slow slip events is predominantly
influenced by the interplay between initial stress states and the extent of pore pressure
perturbations along the faults, rather than the presence of heterogeneous faults. However, our
single VW-patch model does not consider interactions among asperities (e.g., Lui & Lapusta,
2016). Thus, further research incorporating multiple asperities is necessary to comprehensively
investigate the impacts of such heterogeneous faults.

In our reference model, aseismic transients represent smaller source parameters (stress
drop, rupture radius, and moment), decreased source scaling, a lower count of events, and a
longer time span between aseismic events compared to the observations in the Airport sequence
(Figure 7). Due to insufficient geological data for the properties of the Airport fault, we establish
a simple model framework using only one VW patch. The use of a simple model framework can
offer a straightforward simulation and understanding (Lengliné et al., 2023), but it may be the
main cause that the model results did not completely match the observations. The simple
approach does not consider several factors, such as changes in bulk and dilatancy, thermal
pressurization or flash weakening processes, and opening-mode fractures. These factors could
potentially provide additional mechanisms for reducing fluid pressure. Stress drops from
numerical modeling are estimated using different processes compared to those from
observational calculation. We directly estimate the average shear stress changes from the
simulation, whereas stress drops from observational studies are estimated from the averaged
source spectrum recorded from multiple stations (Jeong et al., 2022). Therefore, the accuracy
depends on the number of stations, network coverage resolution, and rupture directivity. In

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addition, stress drop estimates can be biased by inappropriate path correction, especially depth-dependent attenuation factors (Abercrombie et al., 2021).

In this study, we observe that simulated aseismic slips exhibit longer durations (1-3 days) in contrast to the typical seismic signals. These aseismic slips are generally recorded by geodetic instruments or strainmeters (Eyre et al., 2022; Guglielmi et al., 2015; Jiang et al., 2022; Pepin et al., 2022; Staniewicz et al., 2020). Conversely, the waveforms of Airport earthquakes resemble those of typical earthquakes (see Figure S4). To enhance the similarity between the Airport seismic data and our results, we estimate the source parameters of aseismic slips with shorter durations by employing higher thresholds for slip rates, ranging from $10^{-6}$ to $10^{-8}$ m/s (Figure 11). The average durations for thresholds of $10^{-6}$, $10^{-7}$, and $10^{-8}$ m/s are 33.4 minutes, 6.0 hours, and 2.9 days, respectively. Note that numerous events are eliminated due to the increased thresholds. Figure 11 shows that increasing the threshold leads to reduced moments and source radii, while the stress drops are increased, revealing more dynamic properties associated with the shorter durations (see also Figure S5). The average stress drops are estimated as 1.39, 1.14, and 0.80 MPa for thresholds ranging from $10^{-6}$ to $10^{-8}$ m/s. Despite these alterations, the scaling relationships remain largely consistent with values of $M_0 \propto r_0^{3.7}$, $M_0 \propto r_0^{3.69}$, and $M_0 \propto r_0^{3.78}$, respectively. Through the analysis, we infer that if aseismic slips are recorded by real-world seismometers, the resulting stress drops could be lower ($< 1.5$ MPa) and follow non-self-similar scaling, similar to those observed in the Airport sequence. While these durations are still longer than the durations of recorded seismograms, we suggest that the lower stress drop events within the Airport sequence may represent less dynamic ruptures involved in a wide spectrum of slip modes as shown in our simulations.

**Figure 11.** Comparison of source parameters estimated from aseismic slips with higher thresholds of slip rates: $10^{-6}$, $10^{-7}$, and $10^{-8}$ m/s denoted by stars, triangles, and squares, respectively. The green diamonds and orange circles represent the source parameters calculated from the Airport sequence and original threshold ($1.46 \times 10^{-9}$ m/s). As thresholds increase, smaller moments and source radii emerge, accompanied by increased stress drops.
We use constant permeability (1.0 × 10^{-15} \text{ m}^2) along the fault, considering the relatively limited injection duration, shorter simulation time, and computational efficiency. However, several studies have proposed that permeability changes can contribute to slow slip earthquakes and variations in fluid-induced seismicity (Khajehdehi et al., 2022, Marguin & Simpson, 2023). To investigate the effect of permeability changes, we conduct an additional simulation with a simple permeability evolution. Based on the findings that aseismic slip results in an increase in permeability on the fault (Zhu et al., 2020), we assume that the permeability within the VW asperity is increased by an order of magnitude to 1.0 × 10^{-14} \text{ m}^2 after the peak of the second aseismic slip. The enhanced permeability leads to a slightly advanced seismic rupture by ~0.03 years and yields a stress drop that is ~0.04 MPa higher than the reference case (Figure 12). Thus, it appears that permeability changes do not significantly impact our modeling results.

Figure 12. Comparison between simulations incorporating an increased permeability after the second aseismic slip (red) and simulations with the original constant permeability (blue). The permeability enhancement results in an advanced seismic rupture.

If the transition from aseismic to seismic behavior is a general phenomenon, then aseismic slip can be a precursor to the occurrence of seismic rupture. Danré et al. (2022) suggest that aseismic slip observed in induced seismicity has the same mechanism as the natural slow earthquakes that generally occur in a subduction zone. This finding suggests that we can potentially extend our findings from the study of induced earthquakes with known fluid input to understand the detailed fluid effect on natural earthquake slip at large. For instance, the fluid volume-seismicity relation estimated from induced earthquakes has been applied to represent the dynamic behavior of slab-derived fluid associated with natural earthquake swarms (Mukuhira et al., 2022). Hence, modeling of induced seismicity can improve our understanding of pore
pressure effects on earthquake swarms in natural conditions and can provide critical insights for earthquake evolution and timing prediction as a precursor to large earthquakes (Ruhl et al., 2016).

In this study, we investigate multiple injection factors responsible for inducing both aseismic and seismic events, which are critical for assessing the potential of induced seismicity. Simulation results suggest that the interaction between the amount of pore pressure perturbations and the stress state during the interseismic period can be critical in assessing the potential for inducing earthquakes. To minimize fluid-injection effects, operations with balanced fluid injection conditions seem to produce fewer damages from induced seismic events, such as injecting further away from pre-existing faults, adopting shorter injection durations, using smaller injection volumes, and beginning injection during the early or middle phases of the interseismic period. Some observations have indicated that cyclic injection, repeating short injection durations and rest periods, can reduce the magnitude of earthquakes (Yoon et al., 2015; Ji et al., 2023). Our modeling results complement the cyclic injection scheme and may provide insight into practical design for injection related industries. More accurate faulting models that can be used to better constrain the physical cause of anthropogenically induced earthquakes will provide local constraints that supplement regional probabilistic seismic hazard maps and the basis to introduce regulations controlling the amount of fluid injection.

5. Conclusions

In this 2D numerical modeling study, we investigate the interplay between fluid pressure perturbations, aseismic slip, and seismic rupture throughout the earthquake cycle. Our model focuses on understanding the dynamics of injection-induced earthquakes near the DFW Airport by incorporating spatial variations in fluid pressures and slow tectonic loading. The results show that changes in stress caused by injected fluid pressure can trigger aseismic slips and subsequently advance or delay subsequent seismic ruptures compared to models without fluid injection. Stress drops associated with aseismic slip are generally lower than those resulting from seismic rupture. Moreover, these stress drops exhibit a linear increase with simulation time, seismic moment, distance from the injection point, and averaged pore pressure perturbation, suggesting a possible link to the non-self-similar scaling observed in the Airport sequence. The simulations with various injection operations and fault frictional parameters show that the amount of pore pressure perturbations and stress states during the interseismic period influence the onset, number, recurrence intervals, and source parameters of aseismic slips. However, the relationship between stress drops and moments remains consistent, following $M_0 \propto r_0^{3.6}$ for all aseismic slips and $M_0 \propto r_0^{4.3}$ for total simulated events, irrespective of modifications to input parameters. Based on the similar scaling observed in the Airport sequence, $M_0 \propto r_0^{4.7}$, we suggest that the lower stress drop events in the vicinity of the Airport might signify less dynamic ruptures that exhibit characteristics resembling slow slip events shown in our simulations.

Data Availability Statement

No data were used in this study. Simulation results are available in the tables provided by the online version of supporting information.
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