

Article

Perforation and Loading Parametric Effects on Dynamic Rock Deformation and Damage Behaviors During Initial Fracturing Stages in Tight Reservoirs

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Abstract: Hydraulic fracturing technologies introduce deformation, damage, and fractures into tight oil reservoirs, which facilitates the production of hydrocarbons for the economic development of such fields. In addition to typical plug-and-perf fracturing techniques where the loading is usually increased with time, some field attempts have been made where cyclic and periodically dynamic loadings were used to create damage and failure in the reservoir rocks. This paper presents a numerical analysis of rock deformation and damage behaviors induced by dynamic loadings, specifically focusing on the beginning stage of hydraulic fracturing in tight oil reservoirs. An elasto-viscoplastic model based on finite element methods was utilized to simulate the effects of varying loading and perforation parameters. Three distinct scenarios were modeled: a single perforation, multiple perforations, and a single perforation with greater periodical loading magnitudes. The study characterized the spatial and temporal evolution of plastic strain, displacement, acceleration, and strain rate in rock formations. The analysis revealed that the plastic effects were highly localized around the perforations in all scenarios. The acceleration magnitudes were highly cyclic, while locations away from the perforations experienced an accumulation of acceleration magnitudes. The strain rate and induced plasticity were also highly correlated with the loading magnitude. The findings demonstrate that increasing the perforation number or loading amplitude significantly influences the deformation magnitudes, dynamic response patterns, and plastic strain accumulation. These insights provide a reference for optimizing the perforation and fracturing parameters during the development of tight oil reservoirs.

Keywords: hydraulic fracturing; numerical analysis; finite element method; periodically dynamic loading; elasto-viscoplastic model



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1. Introduction

Hydraulic fracturing has been widely used in the development of tight oil reservoirs. Hydraulic fractures help to establish high-permeability channels for oil and gas fluid flows in low-permeability reservoirs. In some scenarios, pulsated hydraulic fracturing designs with cyclic and periodical loading patterns are considered since this technique can facilitate loading-induced rock deformation and damage, which helps the formation

of main fractures during hydraulic fracturing treatments. Rock deformation and rock failure under complex loading conditions are very relevant in hydraulic fracturing-related geomechanics. Accurately quantifying and characterizing these processes is important for optimizing hydraulic fracturing operations and enhancing productivity of tight oil reservoir wells.

In order to improve our understanding of these behaviors, recent studies have focused on experimental methods, numerical simulations, and the integration of multiple approaches to provide comprehensive insights into the rock mechanical responses to various types of loadings associated with tight oil development. The relevant experimental studies focused on the anisotropic responsive patterns, compression testing techniques, shearing and hydrostatic loadings, and the use of CT imaging for better visualization of the deformation and damage. Togashi et al. [1] introduced an experimental method to characterize anisotropic mechanical responses by measuring deformation magnitudes at different orientations in individual tests. This approach has advanced the understanding of anisotropic behavior in rock mechanics, which is crucial for predicting the response of reservoir rocks under complex loading conditions. Single-stage and multi-stage compression tests were compared to analyze induced damage in rock samples. This comparison quantified the importance of considering the loading path when evaluating rock strength and deformation properties. It also helped in calibrating the constitutive models used in numerical simulations [2]. Kluge et al. [3] discussed a method to evaluate shear failures in rock samples under hydrostatic loads, emphasizing the effect of hydromechanical interactions in rock deformation. This study improved our understanding of failure mechanisms in reservoir rocks experiencing high-pressure fluid injections. In another study on rock mechanical heterogeneities, Chen et al. [4] conducted numerical and experimental studies on the highly heterogeneous mechanical responses in tight rock samples. The similarity between the experimental data and numerical simulation results confirmed the reliability of their analyses. In a similar approach, Baumgarten and Konietzky [5] demonstrated the advantages of combining experimental and numerical methods to characterize post-failure behaviors. In addition to compression tests and numerical simulations, the visualization of deformation and failure is also a helpful strategy. Guo et al. [6] utilized computed tomography (CT) alongside triaxial compressional tests to better understand heterogeneous mechanical responses and damage accumulations in heterogeneous reservoir rocks. This integration of imaging techniques enhanced the resolution, accuracy, and reliability of rock deformation and damage quantification.

The derivation of governing equations for dynamic rock mechanical responses is also very relevant. An analytical solution in Laplace–Fourier space was derived to capture the transient behaviors of the poro-elasto-dynamic field in near-well reservoir rocks. This analytical approach provides a framework for understanding the dynamic responses of reservoir rocks under various loading conditions, including hydraulic fracturing [7]. In a series of modeling studies for the rock mechanical behaviors under cyclic and periodic fracturing in tight reservoir rocks, Hou et al. [8–10] characterized the pressure and stress propagations in tight reservoir rocks under dynamic loadings induced by pulsating hydraulic fracturing where oscillatory loadings were exerted. The results showed that dynamic loadings help to induce damage accumulation and fracture initiation, with pressure wave propagation closely related to the rock mechanical properties and cyclic loading frequencies. Fakhimi et al. [11] utilized physical and numerical methods to analyze rock strength under impact and dynamic loads based on Split Hopkinson Pressure Bar (SHPB) testing. Kim et al. [12] then examined the rock skeleton acceleration behaviors caused by the inertia effect of lateral confinement in SHPB testing, providing insights into the strain rates caused by dynamic impact loads. These studies have contributed to our under-

standing of the behavior of rocks under high strain and dynamic loading conditions. In their numerical investigation, Prabhu and Qiu [13] employed the discrete element method (DEM) to simulate stress–strain relationships for solids under impact loads. This numerical study considered both stress equilibrium and nonequilibrium assumptions, offering a comprehensive perspective on the mechanical response of rocks under dynamic conditions. Based on experimental and numerical understanding of the mechanical responses induced by dynamic loadings, the implications for brittleness and fracability quantification were also determined. Lecampion et al. [14], Chen et al. [15], and Guo et al. [16] discussed the importance of rock mechanical responsive patterns in governing brittleness and fracability. Zhang et al. [17] proposed an experimental method to quantify the effect of loading rates and lithologies on acoustic emission, denoted by Kaiser effects, during in situ stress measurements. The study established loading rate selection criteria, which are crucial for accurate stress measurements in reservoir rocks. Wang et al. [18] and Wei et al. [19] discussed strategies for optimizing laboratory determinations of formation damage, where permeability evolution was used as an index. Their studies provide references for optimizing perforation designs and modeling fracture initiation processes, which are essential for enhancing hydraulic fracturing efficiency. In addition, the creep effects in reservoir rocks during hydraulic fracturing are also considered, where the time-dependent behavior can have an impact on fracture closure and fracture width evolution [20].

Based on the literature review, it can be seen that recent studies on rock deformation and failure under various loading conditions have advanced our understanding of the geomechanical behaviors in reservoir rocks under dynamic and pulsated loadings. Experimental approaches, numerical simulations, and their integration have provided more accurate and reliable insights into the mechanical responses of rocks, which are crucial for optimizing hydraulic fracturing operations. In addition to this progress, it has been noted that the numerical investigation of rock mechanical responses to cyclic and dynamic loading during fracturing can be improved by examining the effect of the hydraulic fracturing perforation parameters.

In this study, an elasto-viscoplastic model was used to examine the rock deformation and damage behaviors under dynamic loading caused by hydraulic fracturing in tight reservoir rocks. Both elastic and viscoplastic behaviors are captured in the model while considering the inertia effect. The stress, strain, and acceleration results from several scenarios with various perforation configurations and loading parameters were obtained. This study provides insights into the optimization of hydraulic fracturing parameters and perforation parameters during the development of tight oil reservoirs.

2. Numerical Model

In this study, a numerical model that considers dynamics and elasto-viscoplastic behaviors was used for the quantitative analyses. The dynamic hydraulic fracturing load on tight oil reservoir rocks was treated as a boundary load on the solid rock. The boundary load also evolved with time. This study was limited to the very early stages of the dynamic loading to reflect the initial rock deformation and failure, which can be used to quantify the ease of main fracture formation. The plane stress assumption was used in this model. In addition, this model focused on the solid mechanical field in the reservoir rock.

The basic momentum balance equation is

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{b} \quad (1)$$

where $\mathbf{u}$ is the displacement; $\boldsymbol{\sigma}$ is the stress; ρ is the rock density; and $\mathbf{b}$ is the body force (gravity in this scenario). The time derivative term is used to calculate the acceleration and the inertial effect.

The dynamic boundary load introduced by fracturing on the reservoir rock is depicted by

$$\boldsymbol{\sigma} \cdot \mathbf{n} = \mathbf{t} \quad (2)$$

$$\boldsymbol{\sigma} \cdot \mathbf{n} = 0 \quad (3)$$

where $\mathbf{t}$ is used to denote the evolving loading condition. It is prescribed as a boundary condition as a function of time in Equation (2). Similarly, Equation (3) indicates a fixed boundary.

After the exertion of loading, in the elastic regime, the linear stress and strain relationship is used for calculation. When it enters plasticity, the Drucker–Prager criterion is involved:

$$F = \sqrt{J_2} + \alpha I_1 - k \quad (4)$$

$$\alpha = \frac{\sin \phi}{\sqrt{3}} \quad (5)$$

$$k = \frac{2c \cdot \cos \phi}{\sqrt{3}} \quad (6)$$

Equation (4) shows the yielding criterion F where invariant I_1 and invariant J_2 are involved. In this study, the Drucker–Prager criterion is matched to the Mohr–Coulomb criterion through the two constants α and k , as shown in Equations (5) and (6). As key Mohr–Coulomb constants, ϕ is the internal friction angle and c is the cohesion.

Since the dissipation problem is involved in solving for the dynamic response in reservoir rocks, special numerical strategies, as shown in Equations (7)–(11), are used.

$$u_{n+1} = u_n + \Delta t \frac{du}{dt}_n + \frac{\Delta t^2}{2} \left((1 - 2\beta) \frac{d^2u}{dt^2}_n + 2\beta \frac{d^2u}{dt^2}_{n+1} \right) \quad (7)$$

$$\frac{du}{dt}_{n+1} = \frac{du}{dt}_n + \Delta t \left((1 - \gamma) \frac{d^2u}{dt^2}_n + \gamma \frac{d^2u}{dt^2}_{n+1} \right) \quad (8)$$

$$\frac{d^2u}{dt^2}_{n+1} = M^{-1} \left(f_{n+1} - K u_{n+1} - C \frac{du}{dt}_{n+1} \right) \quad (9)$$

$$u_{n+1} = u_n + \Delta t \frac{du}{dt}_n + \Delta t^2 \left(\left(\frac{1}{2} - \beta \right) \frac{d^2u}{dt^2}_n + \beta \frac{d^2u}{dt^2}_{n+1} \right) \quad (10)$$

$$\frac{du}{dt}_{n+1} = \frac{du}{dt}_n + \Delta t \left((1 - \gamma) \frac{d^2u}{dt^2}_n + \gamma \frac{d^2u}{dt^2}_{n+1} \right) \quad (11)$$

where u is the displacement; subscripts n and $n + 1$ are used to denote the time steps; $\frac{d^2u}{dt^2}$ is the solid acceleration; Δt is the time step size; β and γ are numerical parameters denoting damping and stability during the solution; M is the mass matrix; f is the external force related to $\mathbf{t}$; K is a stiffness matrix; and C is a damping matrix.

Equation (7) is used to update the displacement field. It computes the displacement at the next time step based on the current position, velocity, and acceleration. It incorporates the linear motion governed by the current velocities and the acceleration effect. Equation (8) updates the velocity of the system for the next time step. It integrates the acceleration effects into the velocity, accounting for the change due to the forces applied during the time step. Equation (9) is the acceleration update that is essential for determining the dynamic response of the system to the forces applied. It solves the balance

of forces by considering the inertia, the damping effect, and the stiffness of the system, which are used to understand how the reservoir rocks respond under dynamic loads introduced by fracturing. Equations (10) and (11) are used to improve the predictions made by Equations (7)–(9) by incorporating additional parameters that control numerical damping and oscillations. They balance the current displacement and velocity with the predicted accelerations to provide updated estimates of these quantities

3. Results and Discussion

3.1. Base Case with a Single Perforation

The numerical model was established based on a tight oil reservoir in the Jimsar Sag in the Junggar Basin, northwest China. In the target area, the primary rock types are sandy dolomite, lithic feldspar fine-grained sandstone, and calcarenite. The reservoir rocks are characterized by poor sorting and sub-angular grains, with a high content of cement and matrix materials such as clay, kaolinite, and calcite. These characteristics lead to an average porosity of 7% and an average permeability of 1 mD.

First, the base case considering the dynamic loadings exerted at the beginning stage during fracturing was investigated. A 2D circular domain was simulated, and the radius was 0.5 m. The perforation had a radius of 0.5 cm. The reservoir rock had a Young's modulus of 50 GPa, a Poisson's ratio of 0.2, and a density of 2500 kg/m³. The dynamic loading was described by a sine function oscillating between 0 MPa and 70 MPa. The loading occurred at the perforation at the center of the domain. The was is 0.1 ms and the phase was -90° . The baseline of the function was 35 MPa and the amplitude was also 35 MPa. The entire numerical simulation time was 1 ms. The outer boundary was a roller boundary while the inner boundary (the perforation) was subjected to a cyclic loading.

In the numerical analysis, when characterizing the dynamic rock skeleton response, the temporal effect was also considered in the constitutive equation. The temporal effect on strain is described by

$$\frac{\partial \varepsilon}{\partial t} = \dot{\varepsilon}_p^{\dot{q}} \mathbf{n}^D \quad (12)$$

$$\mathbf{n}^D = \frac{\partial F_y}{\partial \sigma} \quad (13)$$

$$\dot{\varepsilon}_p^{\dot{q}} = A \left\langle \frac{F_y}{\sigma_{ref}} \right\rangle \quad (14)$$

where $\dot{\varepsilon}_p^{\dot{q}}$ is the strain rate; $\mathbf{n}^D$ is the strain rate direction; F_y is the yield function related to the failure criterion in Equation (4); A is the rate coefficient governing the temporal change in strain; and $\langle \cdot \rangle$ is the Macaulay brackets related to the failure criterion. Therefore, the loading-induced strain can be characterized by viscoplastic strain considering the temporal effect. Thus, a Perzyna-type viscoplastic model was employed while a von Mises-based yield function was utilized. Linear and isotropic hardening was assumed for plastic behaviors, while kinematic hardening was neglected.

Due to the highly nonlinear nature of the model, the numerical simulation did not rapidly and monotonically converge. In the 2D mesh, unstructured triangles were used for gridding. In the finite element problem, the number of degrees of freedom was 992,544. The memory usage reached 5.07 GB, and it took 3224 s to finish the base case using a 13th Gen Intel Core i9-13900H (2.60 GHz) processor. This indicates that, although the computational load was relatively high, the numerical strategy was practical, viable, and relatively convenient.

Based on the aforementioned setup, the numerical results of the base case were obtained. Figure 1 shows the 2D distribution of plastic strain, displacement, acceleration in

rock skeletons, and the x component of the strain rate. The presented results are after 1 ms of exerting the dynamic loadings. The results show that the induced damage (in terms of viscoplastic strain) was highly localized around the perforation, and the induced damage did not propagate into the far field. The detailed spatial distribution of viscoplastic strain is visualized in the line plots below. The displacement result demonstrated a significant oscillatory pattern at 1 ms, which was only captured by the dynamic constitutive equation in this model. This was different from the monotonic displacement distribution simulated by the models that relied on static or quasi-static assumptions. At 1 ms, the greatest displacement reached 9×10^{-7} m around 15 cm away from the perforation. As we move away from the perforation, the displacement magnitude dropped to less than 1×10^{-7} m; it then bounced back to 5×10^{-7} m, followed by a sudden decrease. The oscillatory displacement result indicates the complexity of the spatial and temporal evolution of the dynamic loading-induced deformation. Similar trends were also observed in the acceleration results: high acceleration magnitudes around 1.4×10^4 m/s² were observed near the wellbore, while the oscillation of the acceleration magnitude was observed moving toward the far field. Based on the 2D results, the oscillatory distributions of the acceleration and displacement were correlated. The x component of the strain rate was then added to the plots. Both positive strain rates and negative strain rates were captured within the domain, indicating that the deformation rate gradients oscillated between the perforation and the far field. It was also noted that the greatest strain rate (x component) magnitudes were obtained in the x direction, implying an orientation-dependent strain rate response pattern.

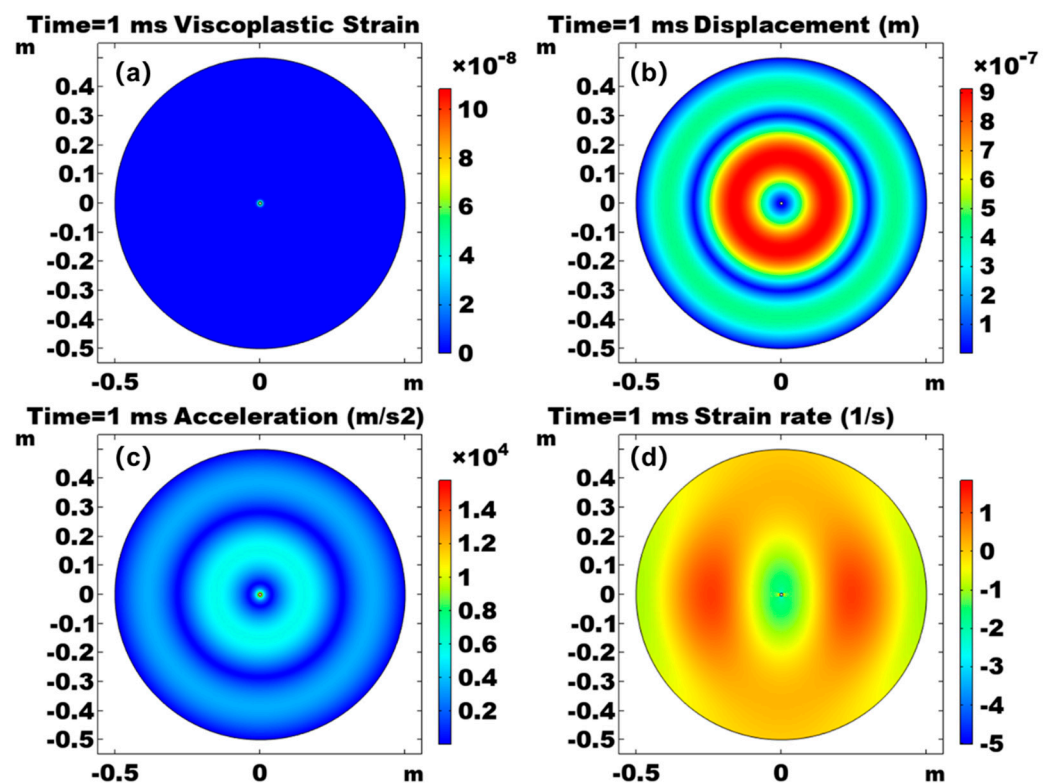


Figure 1. The distribution of the plastic strain, displacement, rock skeleton acceleration, and strain rate in the x direction after 1 ms in the base case. (a) Viscoplastic Strain, (b) Displacement, (c) Acceleration, (d) Strain rate.

To better present the dynamic effect captured by the model in this study, a comparison was made between the displacement and strain rate results and typical results of hydraulic fracturing-induced near-well deformation and stress results based on quasi-static

models [21–25]. The strain and stress responses simulated by the geomechanical models based on quasi-static assumptions tended to oscillate less significantly, and very localized stress concentration was observed at fracture tips. In contrast, the geomechanical response captured by this dynamic model was much more oscillatory and no stress concentration behaviors were observed. The main reason for these differences is that this model can capture the time-dependent behaviors and wave propagation effects. The dynamic model introduced in this study can account for the inertia effects and damping effects, while previous models based on quasi-static assumptions produce instantaneous equilibrium states.

The overall displacement response decreased as the distance increased from the wellbore perforation. This phenomenon is governed by the interaction of stress dissipation and geomechanical properties. The fracturing loading generates a large displacement response at and near the perforation. The response evolves nonlinearly with distance. This attenuation occurs due to energy dispersion. Also, the geomechanical behavior transitions from plastic to elastic responses in the surrounding formation with increasing distance.

Figure 2 shows the distribution of the displacement magnitude at wave valley and wave peak timesteps. The wave valley timesteps were at 0.2 ms, 0.4 ms, 0.6 ms, 0.8 ms, and 1 ms, and the wave peak timesteps were at 0.25 ms, 0.45 ms, 0.65 ms, and 0.85 ms. Based on the cyclic dynamic loading condition, the wave valley timesteps corresponded to a boundary loading of 0 MPa (the minimum loading magnitude) and the wave peak timesteps corresponded to a boundary loading of 70 MPa (the maximum loading magnitude). It can be noted that the displacement distribution at the wave valley timesteps was very different from that at the wave peak timesteps. In general, the displacement distribution at the wave valley timesteps was below 90×10^{-8} m, while it reached 90×10^{-7} m at and near the wellbore perforation boundary. However, the distribution magnitude dropped drastically at the wave peak timesteps as we move away from the wellbore perforation. The locations experiencing zero displacement also shifted between the wave valley timesteps and wave peak timesteps, demonstrating a dynamic and cyclic pattern of displacement evolution. The results indicate that the peak boundary load does not necessarily lead to highest overall displacement in the domain, and it primarily affects the near-perforation displacement magnitudes.

In Figure 3, the acceleration magnitude of the rock skeleton at different timesteps (wave valley and wave peak timesteps) between the wellbore perforation and the far field is plotted. At all timesteps, the greatest acceleration magnitude was located at the wellbore perforation boundary. This trend was different from that of displacement in Figure 2. In Figure 2, the displacement represents the accumulation of deformation during the exertion of the cyclic dynamic load, and the dynamic loading magnitude was not directly related to deformation. In contrast, in Figure 3, the acceleration was related to both the boundary loading magnitude and the changing rate of the boundary loading. This means that the acceleration at and near the perforation boundary can be very high even when the boundary loading magnitude is very low. In addition, the distribution of the acceleration magnitude was generally oscillatory. Similar to the displacement magnitude result, the locations with a zero-acceleration magnitude also shifted between different timesteps. The magnitudes could reach very high values, indicating the dynamic response induced by fracturing loading in very short time spans.

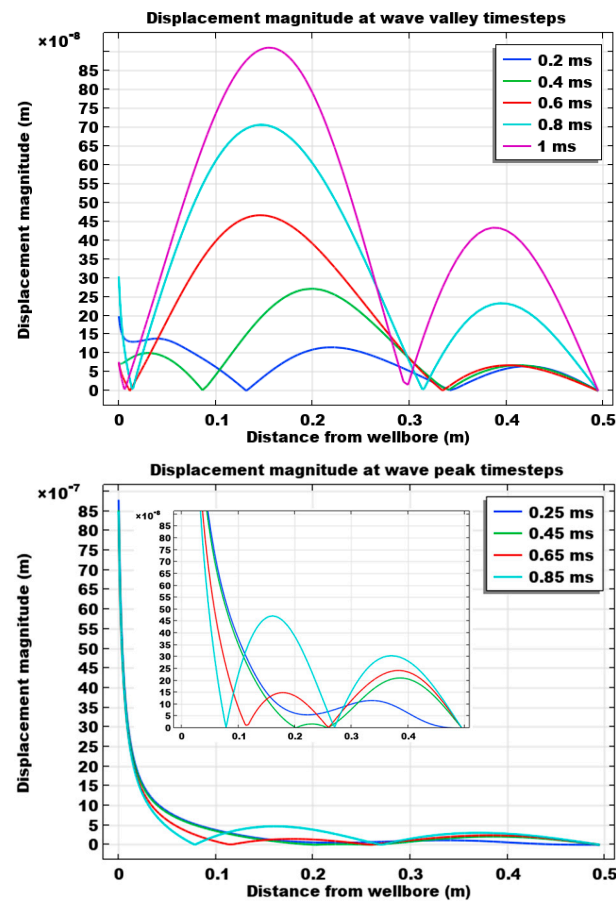


Figure 2. The 1D distribution of the displacement magnitude at different timesteps (wave valley and wave peak timesteps) between the wellbore perforation and the far field.

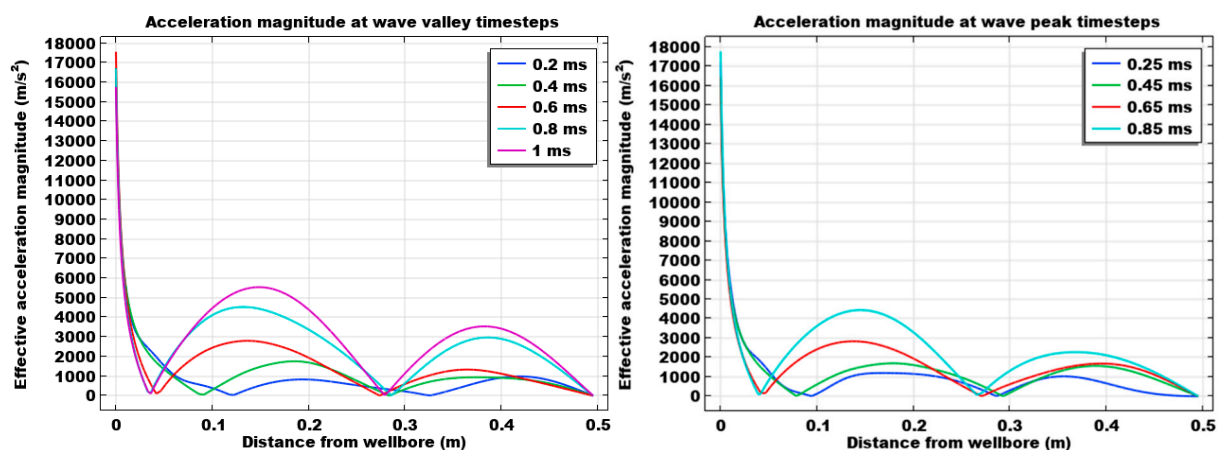


Figure 3. The 1D distribution of the acceleration magnitude at different timesteps (wave valley and wave peak timesteps) between the wellbore perforation and the far field.

The plastic strain results are shown in Figure 4. Unlike the non-monotonic and oscillatory patterns in the previous results, the plastic strain accumulated with time and it evolved monotonically with loading time. However, the plastic region was generally located at and near the wellbore perforation (within 2 cm), indicating that the dynamic loading-induced formation damage only occurred near the perforation. The decrease in plastic strain as we move away from the perforation was significant and it decreased by an order of magnitude. The accumulation of the plastic damage did not oscillate, indicating that the induced plastic deformation is irreversible when the loading is relaxed.

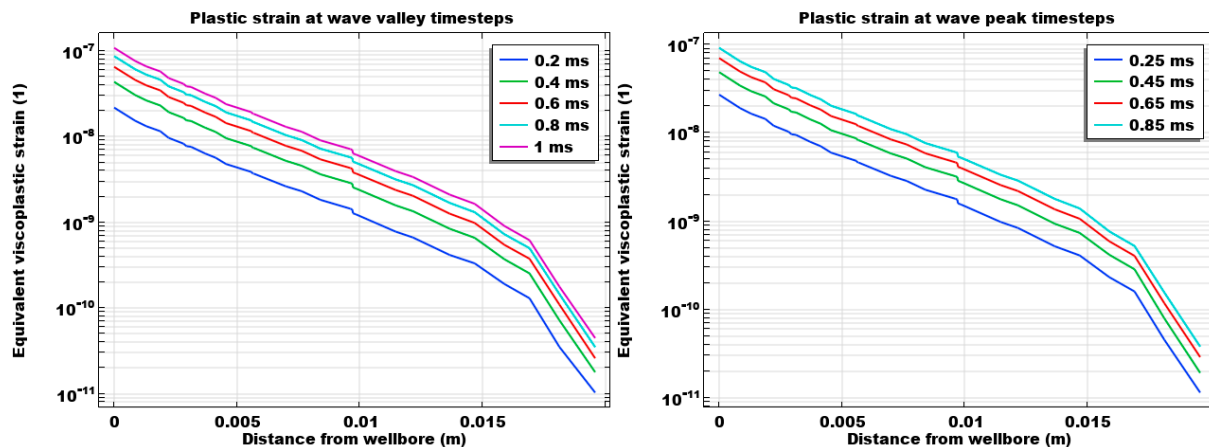


Figure 4. The 1D distribution of the plastic strain at different timesteps (wave valley and wave peak timesteps) near the wellbore perforation.

The previous results showed the spatial distribution at various timesteps. Then, the evolving patterns at several monitoring points were discussed to better demonstrate the temporal evolutions in the system response. Specifically, six monitoring points at (0.005 m, 0 m), (0.02 m, 0 m), (0.04 m, 0 m), (0.06 m, 0 m), (0.08 m, 0 m), and (0.1 m, 0 m) were investigated. Since the results were symmetrical in the circular domain, the selected monitoring points were relatively representative.

In Figure 5, the temporal evolution of the displacement magnitude and acceleration magnitude at six monitoring points at (0.005 m, 0 m), (0.02 m, 0 m), (0.04 m, 0 m), (0.06 m, 0 m), (0.08 m, 0 m), and (0.1 m, 0 m) over 1 ms are plotted. At (0.005 m, 0 m), since it is exactly at the perforation boundary, the displacement evolution was highly oscillatory, and the period was similar to that of sine function-type dynamic boundary loads. With the increase in distance to the perforation, the amplitude of the displacement magnitude curves decreased. Also, the wavy and oscillatory patterns became less distinct, and the period decreased. These trends indicate that the displacement response became less correlated with the dynamic loading cycles as the monitoring point moved away from the perforation. Within 0.5 ms, the displacement amplitude decreased as the monitoring point moved away from the perforation. After 0.5 ms, the amplitude of the curve of the displacement magnitude at (0.1 m, 0 m) was higher than the other monitoring points except for (0.005 m, 0 m).

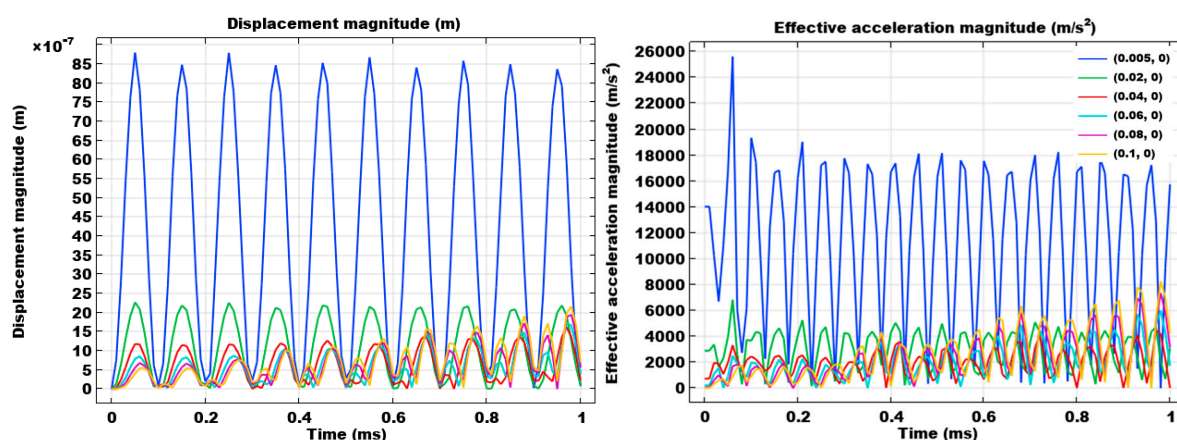


Figure 5. The temporal evolution of the displacement magnitude and acceleration magnitude at six monitoring points at (0.005 m, 0 m), (0.02 m, 0 m), (0.04 m, 0 m), (0.06 m, 0 m), (0.08 m, 0 m), and (0.1 m, 0 m) over 1 ms.

Similar trends were also captured for the temporal evolution results of the acceleration magnitude. The monitoring point at (0.005 m, 0 m) showed the highest acceleration as the dynamic load was directly applied here. However, compared to the displacement magnitude curves, the acceleration magnitude curves were less cyclic and the curve shapes were not regular and periodic. Over time, the acceleration magnitude curves became less periodic, especially at monitoring points far from the perforation.

The results for the temporal evolution of the plastic strain and rate of strain at the monitoring points are shown in Figure 6. Since the evolution of the viscoplastic strain only occurred at and near the wellbore perforation, the plastic strain results at (0.005 m, 0 m) and (0.02 m, 0 m) are plotted while the other monitoring points are not shown. The results indicated that the evolution of plasticity at these locations progressed rapidly in the first 0.2 ms, and then dropped later on. It can also be noted that the increase in plastic strain was highly stepwise, and the step size was closely related to the period and frequency of the dynamic boundary load prescribed by the aforementioned sine function. In addition, when the monitoring point moved from (0.005 m, 0 m) to (0.02 m, 0 m), the plastic strain magnitude dropped significantly and it decreased by an order of magnitude. The stepwise increase in the plastic strain also showed that the plasticity accumulation was monotonic even when the dynamic load was cyclic and oscillatory, and the stepwise pattern was governed by the period of the dynamic loading function. In the strain rate curves, all six monitoring points are discussed since the strain rates were induced at all these locations. The strain rate response was highly periodic and the amplitude decreased with the distance to the perforation. Unlike the previous results that were all positive, the strain rate results were both positive and negative. This indicates a switch between compression and tension induced by the boundary load. The strain rate presented here is the entire strain including the elastic component and the inelastic component, while the plastic strain results are for the inelastic deformation. Also, the strain rate curves at all these locations were relatively regular and the periodic pattern was sustained through the entire simulation time.

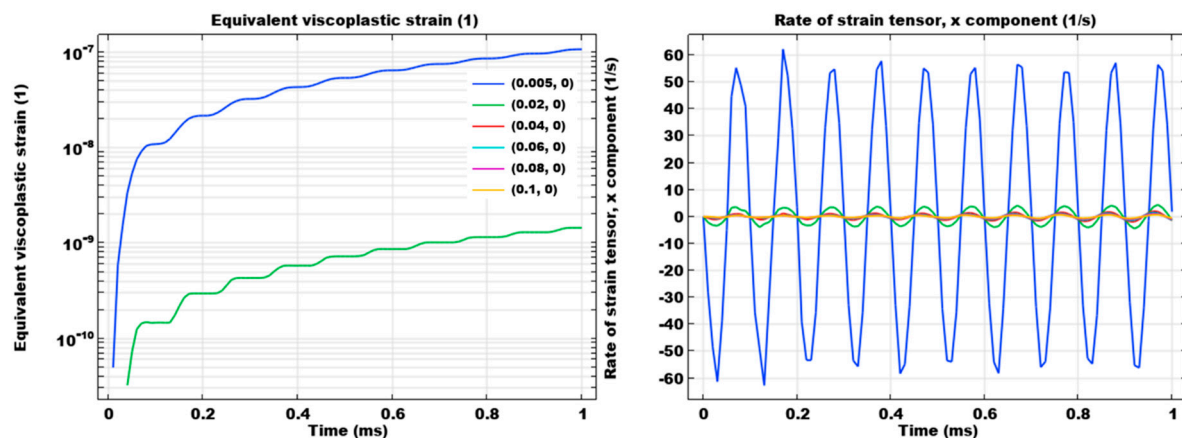


Figure 6. The temporal evolution of the viscoplastic strain at monitoring points at (0.005 m, 0 m) and (0.02 m, 0 m) and the rate of change of the strain tensor at monitoring points at (0.005 m, 0 m), (0.02 m, 0 m), (0.04 m, 0 m), (0.06 m, 0 m), (0.08 m, 0 m), and (0.1 m, 0 m) over 1 ms.

3.2. Multiple Perforations

In the previous case, a single perforation and its induced system response were studied. In this case, multiple perforations were investigated since more than one perforation is usually used in fracturing scenarios in the field. In this study, three perforations with a spacing of 1 cm were studied. Since the radius of the perforation was 0.5 cm, the distance between the center of neighboring perforations was 2 cm. The other parameters were the same as those in the previous base case.

Figure 7 shows the 2D results for the plastic strain, displacement, rock skeleton acceleration, and strain rate in the x direction after 1 ms in the multiple perforation case. In the plastic strain results, although the perforation number increased, the induced plasticity was still at and near the wellbore perforations. The greatest plastic strain was located at the perforation boundaries, and the value reached up to 13×10^{-8} , which was higher than the maximum value in the single-perforation base case. This means that increasing the perforation number can help to increase the induced plastic strain. The difference in the displacement results between this case and the base case was more noticeable. The displacement response was no longer radial as it was in the base case. Instead, it became more responsive in the x direction since more perforations were added in this direction, inducing stronger deformation in the near-perforation areas. Also, the maximum displacement reached 21×10^{-7} m, which was much higher than the maximum displacement of 9×10^{-7} m in the base case. This indicates that increasing the perforation number can effectively lead to greater rock deformation (in terms of displacement magnitude) and the displacement response pattern was also altered. Similar to the displacement, the response of the acceleration magnitudes also became more drastic, and the maximum acceleration magnitude was greater than that of the base case. The strain rate result was also orientation-dependent compared to the base case. Since more perforations were added along the x axis, the maximum value of the strain rate reached above 4 1/s and the minimum value reached -9 1/s at the perforation locations. Note that the results are solely visualized at 1 ms, and the compressive or tensile states were different at different timesteps during the simulation since dynamic loading was employed at the perforation boundaries.

After discussing the 2D spatial results of the system response in the case with multiple perforations, next, we will discuss the temporal evolution at several monitoring points. Since the perforation number was different from the base case, the selected locations of the monitoring points were changed. The six monitoring points in the multiple perforation case were at (0.005 m, 0 m), (0.01 m, 0 m), (0.03 m, 0 m), (0.05 m, 0 m), (0.07 m, 0 m), and (0.09 m, 0 m). The point (0.005 m, 0 m) is on the perforation boundary, which was the same as in the base case. The point (0.01 m, 0 m) is right in between the central and the right perforations. Points (0.03 m, 0 m), (0.05 m, 0 m), (0.07 m, 0 m), and (0.09 m, 0 m) are away from the right perforation.

The temporal evolution of the displacement magnitude, acceleration magnitude, plastic strain, and strain rate at the six monitoring points over 1 ms in the multiple perforation case is shown in Figure 8. All the subplots have the same legend.

The displacement magnitudes at the various locations generally presented oscillatory patterns. The highest displacement magnitude amplitudes were observed at points (0.005 m, 0 m) and (0.03 m, 0 m). This indicates that the perforation boundary and the location next to the right perforation experienced strong deformation oscillations. It was noted that, although it was close to both the central and the right points, the location (0.01 m, 0 m) had a relatively low displacement. This is because this location experienced the system response induced by both neighboring perforations, and the loading effects were canceled out at this location as it was between two neighboring perforations. Also, the displacement magnitude amplitude at these locations tended to increase with time. This indicates that although

the dynamic loading was periodic, the displacement at certain locations increased with time. For all the other monitoring points beyond the right perforation, the displacement magnitude amplitude dropped as the points moved away from the perforation.

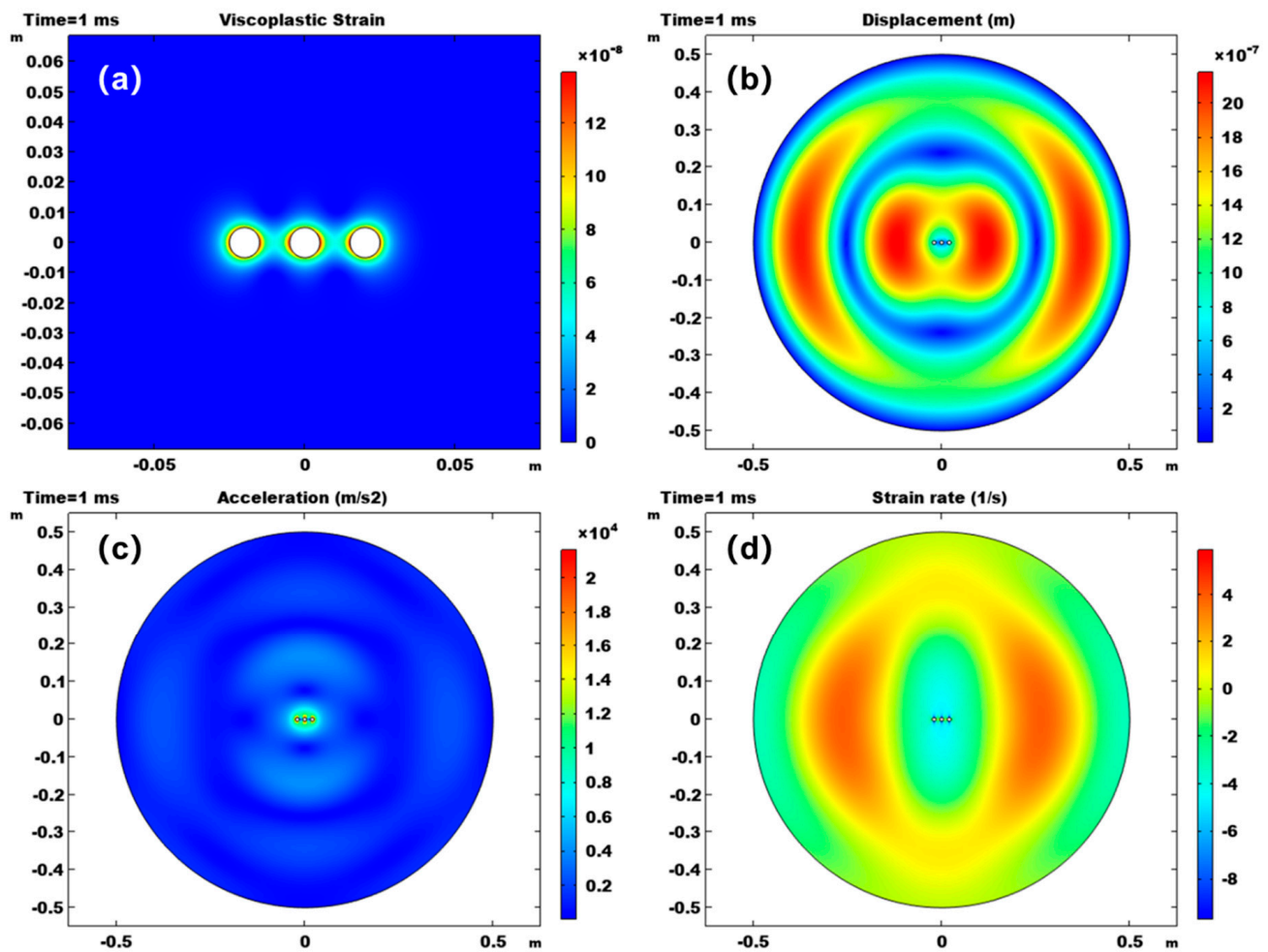


Figure 7. The distribution of the plastic strain, displacement, rock skeleton acceleration, and strain rate in the x direction after 1 ms in the multiple perforation case. (a) Viscoplastic Strain, (b) Displacement, (c) Acceleration, (d) Strain rate.

The acceleration magnitude showed similar trends. In general, the amplitude of the acceleration magnitude tended to increase with time. For example, the acceleration curve at monitoring point (0.09 m, 0 m) did not oscillate significantly at the beginning of the simulation time. However, starting from 0.3 ms, its amplitude started to increase significantly. At the end of the simulation, its peak value was the highest among all the monitoring locations. It was also noted that the green curve for monitoring point (0.01 m, 0 m) had the lowest peak values; the reason for this is similar to that for the response of the displacement curves: the location is in between two neighboring perforations and the loading effect was canceled out. Thus, the acceleration magnitude was actually limited.

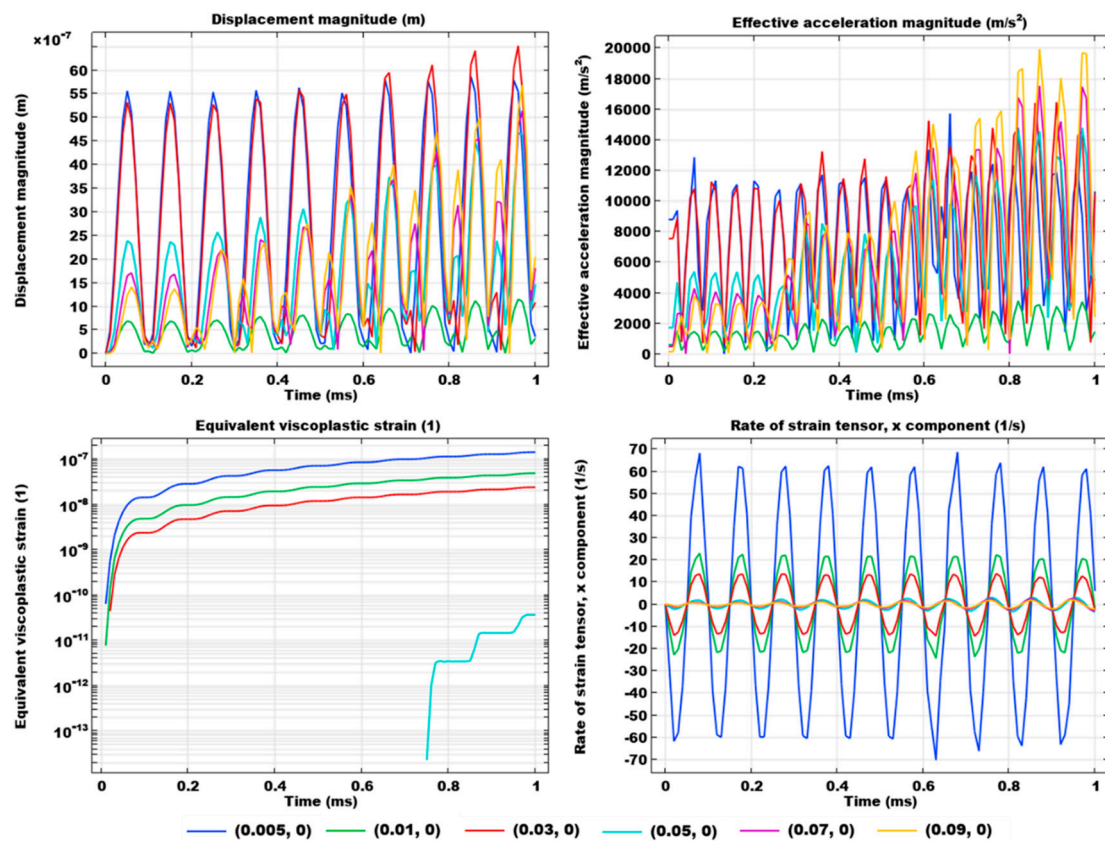


Figure 8. The temporal evolution of the displacement magnitude, acceleration magnitude, plastic strain, and strain rate at six monitoring points during the first 1 ms in the multiple perforation case.

Then, the temporal evolution of plasticity at several monitoring points was determined. Note that due to the limited plastic region, the monitoring points at (0.07 m, 0 m) and (0.09 m, 0 m) are not shown since they are away from the perforation zone. Similar to the base case, the plasticity evolution curves at four locations also showed stepwise changes. The points at (0.005 m, 0 m), (0.01 m, 0 m), and (0.03 m, 0 m) showed an instant plasticity response once the dynamic loading was exerted, while point (0.05 m, 0 m) started to show plasticity after 0.75 ms. This indicates that it takes time for the periodic load to initiate damage formation at locations away from the perforations. Although point (0.01 m, 0 m) had very limited displacement and acceleration responses in the previous discussion, it actually had the second highest plastic strain among the curves. This indicates that the displacement amplitude and acceleration magnitude do not directly govern the plastic deformation. Finally, the rate of change of the strain was also plotted. Similar to the base case, positive and negative values were observed since the rock oscillated between compressive and tensile states. It is important to note that the point (0.01 m, 0 m) had the second highest amplitude, indicating that its strain changing rate was the second highest since it was the closest point to the perforation boundaries other than the point located on the perforation boundary.

3.3. Loading Amplitude

Another parameter (the amplitude of the cyclic boundary loading) is discussed in this section. Compared to the base case in Section 3.1, the only parameter that was changed was the amplitude of the cyclic load. The amplitude increased from 35 MPa to 70 MPa, while other input parameters were all the same.

In Figure 9, the 2D distribution of the plastic strain, displacement, rock skeleton acceleration, and strain rate in the x direction after 1 ms is shown, and it can be compared

with Figure 1 to demonstrate the effect of the boundary load amplitude. Doubling the maximum loading effectively increased the plastic strain from 11×10^{-8} in the base case to 22×10^{-8} in this case. However, the plastic region did not expand significantly after doubling the amplitude, indicating the localized nature of the dynamic loading-induced plasticity. The distribution of the displacement was similarly circular, while the maximum displacement occurred closer to the boundary. Compared to the base case, the maximum displacement at 1 ms was lower, indicating a non-monotonic response. The maximum acceleration magnitude increased from 1.5×10^4 m/s² in the base case to 3.2×10^4 m/s² in this case. This is intuitive since the greater loading amplitude will lead to higher acceleration magnitudes. Similar observations were made in the strain rate results, where the 2D response pattern was very similar to that of the base case, while the magnitudes of the maximum and minimum strain rates both increased, indicating a much more dynamic response caused by the elevated boundary loading magnitude.

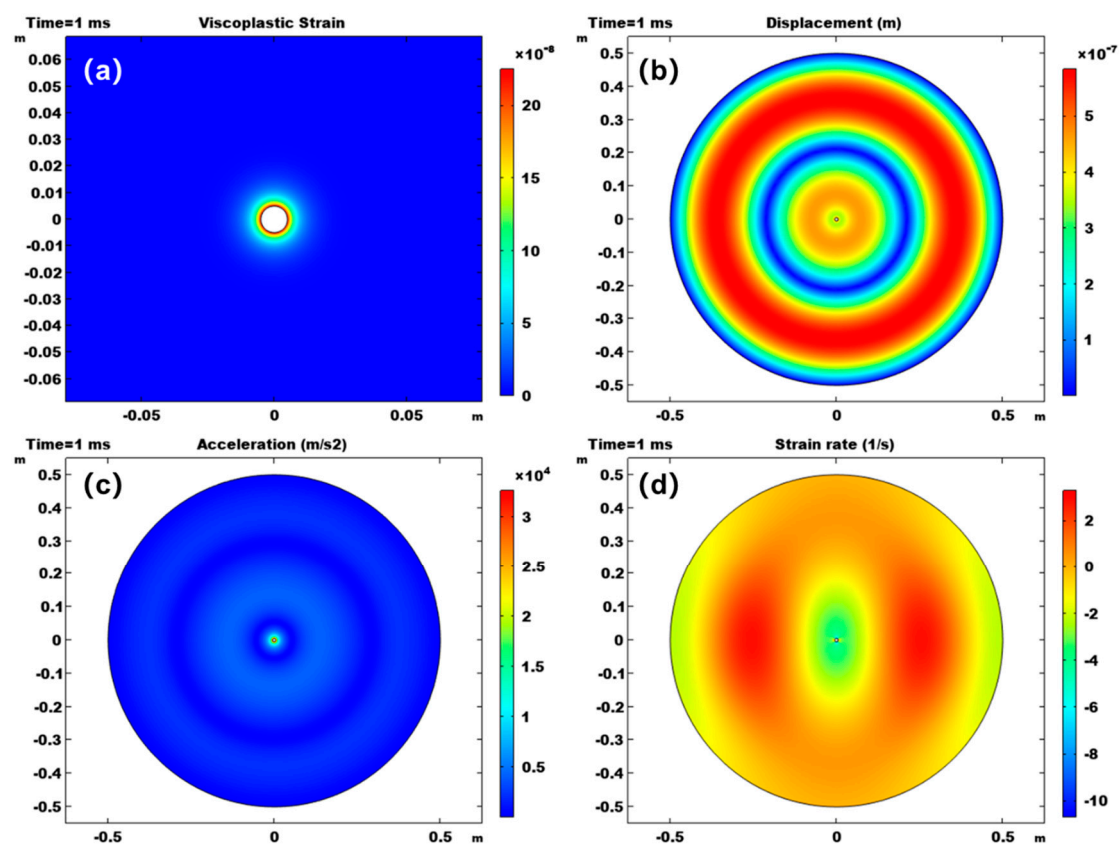


Figure 9. The distribution of the plastic strain, displacement, rock skeleton acceleration, and strain rate in the x direction after 1 ms in the case with an elevated loading amplitude. (a) Viscoplastic Strain, (b) Displacement, (c) Acceleration, (d) Strain rate.

Figure 10 shows the temporal evolution of the displacement magnitude, acceleration magnitude, plastic strain, and strain rate at the six monitoring points over 1 ms in this case with an elevated loading amplitude of 70 MPa. The cyclic evolution pattern of the displacement magnitude was similar to that of the base case, while the peak values were much higher due to the elevated loading magnitude. Similar to the base case, the displacement peaks tended to accumulate at the monitoring points near the outer boundary. Also, the peak of the acceleration magnitude curves became much greater in this case compared to the base case. This was caused by the elevated amplitude of the cyclic load. The acceleration magnitudes at points away from the wellbore perforation also tended to accumulate over time due to the dynamic response in the reservoir rock. In the plastic

strain temporal evolution results, only the points (0.005 m, 0 m) and (0.02 m, 0 m) showed plastic deformation within the time span, which was similar to the base case. This again indicates the localized nature of plasticity accumulation at and near the wellbore perforation. However, the order of magnitude of the plastic strain in this case was higher than that of the base case, indicating that the increased maximum loading magnitude led to greater damage and plasticity. The peak values of the strain rate curves were also roughly doubled in this case, indicating that increasing the impact load can lead to stronger deformation changes.

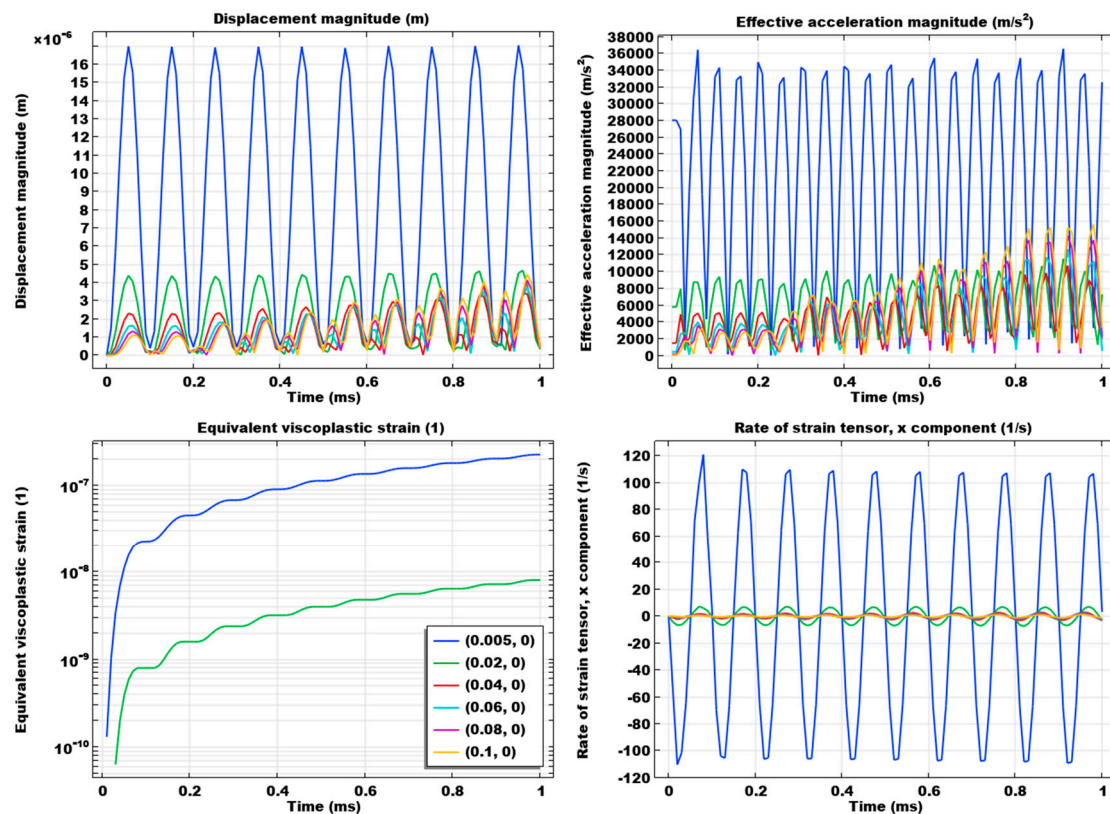


Figure 10. The temporal evolution of the displacement magnitude, acceleration magnitude, plastic strain, and strain rate at the six monitoring points over 1 ms in the case with an elevated loading amplitude.

In general, the numerical results demonstrated that plastic deformation and damage accumulation are highly localized around perforations, indicating that increasing the number of perforations or strategically positioning them closer could enhance reservoir connectivity and fracture initiation efficiency. Additionally, the study showed that cyclic dynamic loading significantly influences rock deformation and damage behaviors, indicating that employing cyclic and pulsating fracturing techniques can improve fracture propagation and complexity compared to monotonic loading methods. Specifically, adjusting the loading amplitudes and frequencies based on the observed correlation between loading magnitude and induced plasticity can optimize fracture initiation and propagation. Field operators can apply these insights by optimizing the perforation spacing and orientation to maximize localized deformation effects. Furthermore, optimizing the dynamic loading parameters such as amplitude and cyclic frequency can enhance fracture efficiency, reduce operational costs, and potentially increase the hydrocarbon recovery rates. Overall, integrating these numerical insights into practical perforation and fracturing strategies can help to improve hydraulic fracturing outcomes in tight oil reservoir development.

4. Conclusions

This study presents a detailed numerical study of the dynamic deformation and plasticity responses of reservoir rocks to cyclic dynamic loading at the beginning stage of hydraulic fracturing in tight oil reservoirs. The study specifically focused on the viscoplastic behaviors induced by cyclic and frequent loading in perforations. The consideration of viscoplastic modeling along with the effects of the perforation parameters is the primary contribution of this work. In conclusion,

- (1) Plastic strain was highly localized near the perforation boundaries, with negligible propagation into the far field within the tight formation. The accumulation of plasticity was monotonic and stepwise, which was determined by the cyclic loading frequency. Doubling the amplitude of cyclic loading significantly increased the plastic strain and acceleration magnitudes while maintaining localized plasticity.
- (2) The displacement and acceleration results exhibited oscillatory behaviors, with the patterns influenced by the proximity to the perforations and the orientation of the applied loads. The displacement response became less significant and periodic as the distance from the wellbore perforation increased.
- (3) In the case with multiple perforations in this study, the amplitudes of displacement and acceleration in the reservoir rock between two neighboring perforations were the lowest since the effects of the synchronized dynamic loads canceled out. However, this location still had the highest plastic deformation and strain rate after the perforation boundary. This means that the plastic deformation was not directly governed by the displacement and acceleration magnitudes.

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