Stress disturbance induced by multiple-well fracturing and its influence on initiation and near-wellbore propagation from infill horizontal perforated borehole

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Abstract. Multiple stage fracturing with multiple pads (MSFMP) is an essential technology for efficient development of unconventional reservoirs, but connecting area of two well pads is still not stimulated. The in-situ stress in the connecting area of well pads would be disturbed after MSFMP, affecting the initiation and near-wellbore propagation of infill horizontal well whose horizontal wellbore deviates greatly from the optimal orientation. Therefore, this paper proposes a method for calculating the stress perturbation caused by MSFMP and then optimizing the perforation parameters of infill horizontal wells in the unstimulated area. The results show that stress disturbance at any position can be calculated based on the stress disturbance model, and then the optimal fracturing interval is obtained in the middle unstimulated area.
Appropriate perforation parameters can significantly decrease the complexity of near-wellbore fractures.

**Key words:** hydraulic fracturing, induced stress, infill well, dislocation theory, discrete lattice method, perforation

1. **Introduction**

The stress shadow (or induced stress) generated due to the formation of hundreds of hydraulic fractures during multiple stage fracturing with multi-well pads (MSFMP), leading to redistribution of the in-situ stress and affecting the propagation of subsequent fractures. To further maximize the recovery, infill horizontal wells whose horizontal wellbore azimuth deviates from the optimal wellbore azimuth (the minimum in-situ stress direction) need to be arranged in the middle unstimulated area (Figure. 1). However, the redistribution of in-situ stresses in the middle unstimulated area is complex after MSFMP of multiple layers.

Many significant efforts have been made on the calculation of stress shadow and its influence on fracture propagation [1–5]. The present stress calculation, however, mainly focuses on the stress shadow caused by single or multiple hydraulic fractures in the same layer, and the influence of stress shadow on fracture initiation and propagation of adjacent fracturing stages or wells is mainly concerned. It is rare to find that stress shadow after MSFMP of multiple layers, especially in the unstimulated connection area of well pads, is calculated. Therefore, it is urgent to establish a quick calculation method of complex stress shadow for MSFMP of multiple layers.

The multi-fracture initiation from perforation tunnels and the competitively non-planar propagation near the wellbore are very complex, in that they are mainly dominated by the rock properties of reservoir and the complicated in-situ stress near the wellbore [6]. Scholars have done a lot of valuable work for fracture propagation of perforation completion in order to understand the complexity of near-wellbore fractures, including the theory and numerical simulation [7–9], and the perforated fracturing experiment [10–12]. However, there are few studies on the three-dimensional fully-coupled numerical model of perforated fracturing considering the multi-scale nature and the systematic study of perforation completion, especially when the horizontal wellbore deviates from the optimal azimuth. It is necessary to clarify the initiation and propagation of multi-tunnel fractures of perforation completion.

Therefore, an integrated method of the calculation of stress shadow induced by MSFMP and the subsequent optimization of helical perforation of inclined infill horizontal wells is proposed based on the infill well in the connecting area of two well pads in the platform H of tight reservoir in Changqing Oilfield, China.

2. **Engineering background**

The target tight reservoirs of platform H in Changqing Oilfield are Chang 7¹, Chang 7² and Chang 7³ layers, with the average burial depth of -1850 m, -1900 m and -1970 m, respectively. The physical properties, mechanical properties and in-situ stresses are listed in Table 1. Three layers are stimulated simultaneously by MSFMP for platform H, and the arrangement of twenty horizontal wells that have been fractured is shown in Figure. 1. The average stage length is 75 m; the stage spacing is 15 m; the cluster number of each stage is 5; the cluster spacing is 15 m; the adjoining well spacing in the same layer is 300 m. An infill horizontal well whose horizontal
wellbore azimuth deviates 73° from the optimal wellbore azimuth is tried to stimulate the middle unstimulated area of the Chang 73 layer for a pilot test. Different from other horizontal wells in this platform H, fracture initiation and propagation of perforated fracturing of infill well would be affected significantly by the stress shadow induced by MSFMP of twenty horizontal wells and the deviation of wellbore azimuth.

![Figure 1. MSFMP of multiple layers in the platform H.](image)

Table 1. In-situ stresses, rock mechanics and physical properties of tight reservoirs

| Parameters                                | Tight shale layer |
|-------------------------------------------|-------------------|
| Vertical stress \(S_v\) (MPa)             | 42                |
| Maximum horizontal principal stress \(S_{\text{Hmax}}\) (MPa) | 36                |
| Minimum horizontal principal stress \(S_{\text{Hmin}}\) (MPa) | 33                |
| Formation pore pressure (MPa)             | 15                |
| Elastic modulus (GPa)                     | 20.5              |
| Poisson's ratio                           | 0.26              |
| Uniaxial compressive strength (MPa)       | 76                |
| Tensile strength (MPa)                    | 4                 |
| Fracture toughness (MPa m\(^{0.5}\))     | 3                 |
| Porosity (%)                              | 9                 |
| Permeability (mD)                         | 0.1               |

3. Stress shadow induced by hydraulic fracturing

3.1. Model establishment

The induced stress components of any point \((x, y, z)\) caused by a dislocation are shown in Eq. (1)\(^{[13]}\).
\[
\begin{align*}
\frac{\sigma_{x'x'}}{\sigma_0} &= b_x' \frac{y'}{r(r+\lambda)} \left[ 1 + \frac{x'^2}{r^2} + \frac{x'^2}{r(r+\lambda)} \right] + b_y' \frac{x'}{r(r+\lambda)} \left[ 1 - \frac{x'^2}{r^2} - \frac{x'^2}{r(r+\lambda)} \right] \\
\frac{\sigma_{x'y'}}{\sigma_0} &= -b_x' \frac{y'}{r(r+\lambda)} \left[ 1 - \frac{y'^2}{r^2} + \frac{y'^2}{r(r+\lambda)} \right] - b_y' \frac{x'}{r(r+\lambda)} \left[ 1 + \frac{y'^2}{r^2} + \frac{y'^2}{r(r+\lambda)} \right] \\
\frac{\sigma_{x'z'}}{\sigma_0} &= b_x' \frac{y'z'}{r^2} \left[ \frac{1}{r^2} + \frac{2y'z'}{r(r+\lambda)} \right] + b_y' \left[ -\frac{y'z'}{r} + \frac{2y'z'}{r(r+\lambda)} \right] \\
\frac{\sigma_{y'x'}}{\sigma_0} &= -b_x' \frac{x'y'}{r^2} + b_y' \left( -\frac{y'}{r} + \frac{x'^2}{r^2} \right) + b_{2x'} \frac{y'(1-v)}{r(r+\lambda)} \\
\frac{\sigma_{y'y'}}{\sigma_0} &= b_x' \frac{y'y'}{r^2} + b_{2y'} \frac{y'(1-v)}{r(r+\lambda)} \\
\frac{\sigma_{y'z'}}{\sigma_0} &= b_x' \frac{y'z'}{r} - \frac{y'z'}{r^2} + b_{2x'} \frac{y'(1-v)}{r(r+\lambda)} \\
\frac{\sigma_{z'x'}}{\sigma_0} &= -b_x' \frac{x'z'}{r^2} + b_{2x'} \frac{x'(1-v)}{r(r+\lambda)} \\
\frac{\sigma_{z'y'}}{\sigma_0} &= b_y' \frac{x'y'}{r^2} - b_{2y'} \frac{x'(1-v)}{r(r+\lambda)} \\
\frac{\sigma_{z'z'}}{\sigma_0} &= b_x' \frac{y'^2}{r^2} + b_{2x'} \frac{x'^2}{r(r+\lambda)} + b_{2y'} \frac{x'^2}{r(r+\lambda)}
\end{align*}
\]

Where \( \sigma_{x'x'}, \sigma_{x'y'}, \sigma_{x'z'}, \sigma_{y'x'}, \sigma_{y'y'}, \sigma_{y'z'}, \sigma_{z'x'}, \) and \( \sigma_{z'z'} \) are induced stress components in the coordinate system of \( x'y'z' \), respectively; \( r \) is the distance from point \( (x', y', z') \) to the coordinate origin \( (0,0,0) \); \( \sigma_0 = E/(8\pi \times (1-v^2)) \), \( \lambda = d - z \), \( r^2 = (x')^2 + (y')^2 + (d - z')^2 \), \( E \) is elastic modulus, \( v \) is Poisson’s ratio, \( d \) is the length of line segment OE, \( b_{2x'}, b_{2y'} \), and \( b_{2z'} \) are the components of the burgers vector in the three directions, respectively.

Assuming that one planar fracture is formed from each perforation cluster, there are five fractures for each stage. According to the microseismic monitoring, the effective half-length, height and width of fracture is 150 m, 60 m and 2 mm, respectively. The mechanical properties of reservoir used in the calculation are shown in Table 1.

### 3.3. Induced stress of the target unstimulated area

Figure 2 shows the induced stress in the middle unstimulated area. Obviously, the distribution of induced stress in the middle unstimulated area is non-homogeneous, but the fluctuation is relatively small, less than 1 MPa. The changes of induced stress (Figure 3) especially for the horizontal stress contrast on different lines \( (y = 200, 100, 0, -100, -200 \text{ m}) \), as shown by the white dashed line in Figure 2a) are selected to quantitatively describe the stress shadow along the infill horizontal well.

**Figure 2.** Contours of induced stresses components \( S_{xx}, S_{yy} \) and \( S_{zz} \) in the middle unstimulated area with fracture width of 2 mm. (a) \( S_{xx} \) at \( z = -1970 \text{ m} \), (b) \( S_{yy} \) at \( z = -1970 \text{ m} \), (c) \( S_{zz} \) at \( z = -1970 \text{ m} \). The black dashed line indicates horizontal wells. The red solid line indicates infill horizontal well. The color column indicates the magnitude of induced stress.
Figure 3. Variation of induced stress components along different lines of (a) $y = 200$ m, (b) $y = 100$ m, (c) $y = 0$ m, (d) $y = -100$ m, and (e) $y = -200$ m with fracture width of 2 mm. (f) Regional division of the middle unstimulated area at $z = -1970$ m.

From Figure 3, the induced stress components along different lines changes differently, and it is shown that the minimum horizontal principal stress increases greatly while the change of other components is small, ranging from -0.1 MPa ~ 0.1 MPa. Thus the variation of horizontal stress difference is controlled by the change of $S_{\text{hmin}}$. It is obvious that the curve of the $S_{\text{hmin}}$ variation ($S_{yy}$) with $x$ value changes from double-hump to single-hump shape when lines change from $y = 200$ m to $y = -200$ m, and these trends are related to the asymmetric arrangement of horizontal wells in the south and north pads (Figure 3f). On the whole, the closer to the well row, the greater the increase of $S_{\text{hmin}}$. For example, the increase of $S_{\text{hmin}}$ on
the line \( y = -200 \) m or \( y = 200 \) m reaches 0.6 MPa, which is 50% higher than that on the line \( y = 0 \) m (0.4 MPa).

On the basis of the position of stimulated area and the variation of \( S_{\text{min}} \) on different lines of the target layer (\( z = -1970 \) m), the middle unstimulated area is divided into five zones (zones 1 ~ 5 in Figure. 3f). It is apparent that the horizontal stress difference in zone 2 has the largest reduction and is relatively stable, and thus is the preferred fracturing interval of infill horizontal well. Compared with the original horizontal stress difference, there is little variation of horizontal stress difference in zones 1 and 5, while fluctuates greatly in zones 3 and 4. To sum up, the infill well should be preferentially arranged in zone 2 with the greatest decrease of horizontal stress difference (0.5 MPa), which is beneficial to fracture propagation of deviated infill well.

4. Initiation and propagation of infill horizontal perforated wellbores

4.1 Numerical program

The discrete lattice method is applied to modelling hydraulic fracturing. The detail description of this method is able to be found in [14–16]. A three-dimensional numerical model of perforated fracturing for the infill horizontal well in the middle area is established (Figure. 4) based on the discrete lattice method. The numerical simulation program is shown in Table 2. The model sample is a cube with side length of 1.83 m. The in-situ stress, rock mechanical and physical properties in the model are shown in Table 1. The horizontal stress difference (2.5 MPa) after MSFMP in the middle area instead of the original difference of 3 MPa is adopted, so as to reflect the contribution of stress perturbation on fracture behaviors. The injection rate per cluster is 1.2 m³/min; there are 6 tunnels for each cluster; the phase angle is 60°, the orientation of the first perforation tunnel is along the vertical stress (\( S_v \)) direction; the perforation density is 16 tunnels/m; the perforation depth is 300 mm and the perforation diameter is 15 mm. The angle between the horizontal wellbore and the optimal azimuth (\( S_{\text{min}} \) direction) is 73°. The slick water with a viscosity of 5 mPa.s is used as fracturing fluid.

![Figure 4](image_url)

**Figure 4.** Three-dimensional numerical model of (a) helical perforation and (b) oriented perforation. (c) Deviation angle between horizontal wellbore and \( S_{\text{min}} \) direction is 73°.

4.2 Fracture initiation and propagation of perforation completion

Two perforation technologies such as helical perforation and oriented perforation are considered, and the orientation of the first perforation tunnel along the vertical direction and the horizontal direction are considered respectively, as shown in programs 1 ~ 4. The near-wellbore fracture morphologies and injection pressures are shown in Figure. 5.
Table 2. Numerical simulation program

| Program | Perforation technology | The first tunnel orientation |
|---------|------------------------|-----------------------------|
| 1       | Helical perforation    | $S_v$ direction             |
| 2       | Helical perforation    | $S_{min}$ direction         |
| 3       | Oriented perforation   | $S_v$ direction             |
| 4       | Oriented perforation   | $S_{min}$ direction         |

![Fracture morphologies](image)

Figure 5. Fracture morphologies under different technologies, (a) helical perforation with the first tunnel orienting the $S_v$ direction, (b) helical perforation with the first tunnel orienting the $S_{min}$ direction, (c) oriented perforation with the first tunnel orienting the $S_v$ direction, (d) oriented perforation with the first tunnel along the $S_{min}$ direction. Red arrow indicates the main propagation direction of fractures.

The main transverse spiral fractures perpendicular to the wellbore are mainly formed for helical perforation, while the main longitudinal fractures parallel to the wellbore are created for oriented perforation (Figure 5). This is because perforation tunnels are close to each other for oriented perforation, which leads to the rapid communication of the adjoining initial axial fractures initiated from the bottom of tunnels, and then the generation of the main longitudinal
fractures (Figure. 5c). In Figure. 5d, the fractures initiated from the three tunnels on the right side of wellbore propagate transversely along the axial direction of the tunnels within one wellbore diameter, and then reorient along the axial direction of the horizontal wellbore, and eventually merge to form a main longitudinal fracture under the influence of in-situ stresses. For helical perforation, the main spiral fractures are created by the linkage of initial transverse fractures initiated from tunnels rather than the longitudinal fractures (Figures. 5a and 5b). It is noted that the main longitudinal fractures for oriented perforation are likely to communicate with adjacent clusters in the near wellbore, resulting in the failure of reservoirs deep-penetration stimulation (Figures. 5c and 5d).

Furthermore, the fracture morphologies with the first tunnel along the S_v direction are better than that with the first tunnel along the S_min direction for different perforation technologies. For example, the smooth transverse fractures (Figure. 5a) of helical perforation are better than the complex fractures consisted of secondary multiple fractures and main transverse fractures (Figure. 5b). The planar longitudinal fractures (Figure. 5c) of oriented perforation are better than the complex fracture with multiple secondary fractures and main longitudinal fractures (Figure. 5d).

5. Conclusions

The mechanical effects caused by fracture openings lead to the stress perturbation (also called as stress shadow) during MSFMP. Due to the asymmetric distribution of horizontal wells of platform H, the stress shadow appears a spatially non-uniform distribution in the middle unstimulated area. The reduction of horizontal stress difference in zone 2 is the largest (0.5 MPa) and relatively stable, and thus zone 2 is the preferred fracturing interval for infill horizontal well.

The helical perforation, especially with the vertical first-tunnel is suggested to form transverse fractures perpendicular to the wellbore when the horizontal wellbore deviates greatly from the optimal azimuth (S_min direction). In contrast, it is unfavorable if the oriented perforation is adopted in that longitudinal fractures parallel to the wellbore are created, easily resulting in the fracture communication between adjacent clusters.

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