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Evaluation of Shadow Stress between Hydraulic Fractures

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ABSTRACT: In order to increase the productivity of extraction of hydrocarbons reservoirs, the well is usually drilled in the direction of the minimum horizontal in situ stress, and hydraulic fractures simultaneously initiate and propagate perpendicular/transverse to the wellbore. In the last decade, more than 10,000 horizontal wells per year have been bored and hydraulically fractured, with up to a hundred hydraulic fractures placed in the horizontal segment of the well. In order to reduce operational cost, it is usual to create several hydraulic fractures at once. The well is there for stimulated in stages, with one stage consisting of a single pumping operation aimed at initiating and propagating simultaneously typically between 3-8 cracks spaced about 10–30 m apart. When the fluid pressure is applied on the surface of the fracture, the crack can propagate in the medium, but the pressure, induced from the fluid injection, may have a negative influence on the extension of adjacent cracks which is stated as shadow or interaction stress. Certainly, an accurate estimation of interaction/shadow stress between the cracks leads to a more optimal design. In this research, the effect of the interaction between the hydraulic cracks with respect to the spacing and the number of cracks on each other and considering the position of the fractures are evaluated using the pseudo traction method. The results are shown that inner-fractures are further affected by shadow stress compared to outer-fractures. On the other hand as the distance of hydraulic fractures increases, shadow stresses decrease. In the last, the results can be useful in determining the optimum number and spacing of cracks in the design of hydraulic fractures.

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1. INTRODUCTION

In the last decade, extensive research has been done on the propagation of single hydraulic fracture, either numerically or analytically, but most recent research has focused on the simultaneous growth of an array of parallel or multiple oriented hydraulic fractures considering interaction and shadow stress between the fractures along a horizontal wellbore [1-2]. In the case of horizontal wells, a detailed investigation of the interaction between hydraulic fractures and stress interference between propagating hydraulic fractures is still required. In this research, the effects of interactions between hydraulic cracks are investigated using this method. Innovation in this study is related to the application of the pseudo-traction method[3] with a fluid presence which is very useful in estimating the interaction stress between cracks. Also, the effect of interaction on multiple hydraulic cracks with respect to their location and number has been analytically investigated in this study.

2. INTERACTING MODEL FOR TWO HYDRAULIC FRACTURES

In order to evaluate the elastic interaction among neighboring hydraulic fractures, we apply the so-called pseudo-traction method developed by Horii and Nemat-Nasser[3].

For simplicity, we first consider an elastic body with two KGD hydraulic fractures i and j with lengths $2\ell_i$ and $2\ell_j$, both of which are subjected to far-field stresses i.e. normal stresses (σ_{11}^{∞}, σ_{22}^{∞}) and shear stress (σ_{12}^{∞}) as shown in Fig. 1. Two coordinate system $x_i y_i$ and $x_j y_j$ are employed that their origins are located at the center of the hydraulic fractures i and j, respectively. Note that the y_i and y_j are taken to be normal to the hydraulic fracture surfaces. The symbols in Fig. 1 are defined as:

θ_{ji}: The inclination angle of x_i to x_j,

ϕ_{ji}: The angle between x_i and center of cracks direction

and, d_{ij}: The distance between origins of hydraulic fracture.

The original problem is elastically examined by decomposing it into three sub-problems; i.e., a homogeneous sub-problem and two sub-problems i and j. In the homogeneous problem there is no crack and the same stresses as the original problem are applied at infinity (i.e. normal stresses σ_{11}^{∞}, σ_{22}^{∞} and shear stress σ_{12}^{∞}), while in each sub-problem i and j, the single hydraulic fracture which is subjected to uniform pressure p_{fi} and p_{fj} respectively, is

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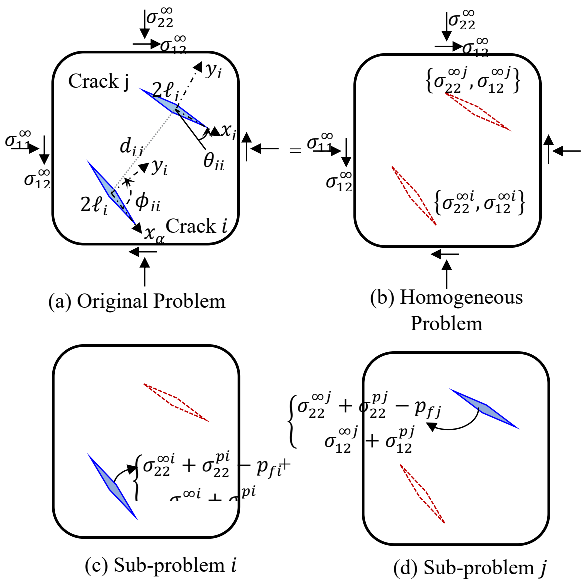


Fig. 1. Process of decomposition of (a) original evolution problem to (b) homogeneous problem and (c,d) sub-problems i and j

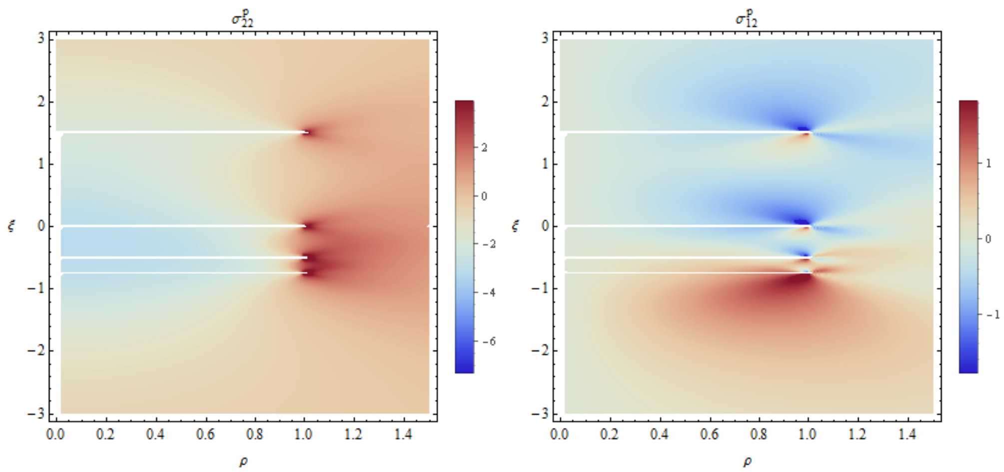


Fig. 2. Distribution of vertical and horizontal stresses vicinity of half-length parallel cracks (drawn using Mathematica version 9.0.0)

contained without far-field stresses, as shown in Fig. 1.

In the sub-problem j, the stress functions with respect to the local coordinate $z_j = x_j + Iy_j$ are given by:

$$\Phi'_j(z_j) = -\frac{1}{2\pi I\sqrt{z_j^2-\ell_j^2}}\int_{-\ell_j}^{\ell_j}\frac{T\sqrt{s^2-\ell_j^2}}{s-z_j}ds,$$
$$\Psi'_j(z_j) = \overline{\Phi'_j(\overline{z_j})} - \Phi'_j(z_j) - z_j\Phi''_j(z_j),$$
$$z_j = x_j + Iy_j \quad j=1,2 \tag{1}$$
$$z_j = d_{ij}e^{I\phi_{ij}} + x_i e^{I\theta_{ij}}, \quad |x_i| \le \ell_j$$
$$T = \left\{\left(\sigma_{22}^{\infty j} + \sigma_{22}^{pj}\right) - I\left(\sigma_{12}^{\infty j} + \sigma_{12}^{pj}\right) - p_{fj}\right\}$$
$$T = T_R + IT_I, \quad T_R = \mathrm{Re}\{T\},\ T_I = \mathrm{Im}\{T\}$$

Where the quantities $\sigma_{22}^{\infty j}$ and $\sigma_{12}^{\infty j}$ are local stresses in j, induced to far-field stresses and σ_{11}^{pj} and σ_{22}^{pj} are "pseudo tractions", which are unknown functions to be determined (for more information please refer to persian paper).

Fig. 2 shows the 2D distribution of stresses in the various directions by considering the effect of the interaction of parallel hydraulic cracks from the exact method. As can be seen, the effect of the shadow stress increases as the distance between the cracks decreases, and this effect emphasis as the cracks approach each other.

3. SPECIAL CASE: EVALUATIONS FOR INTERACTING PARALLEL HYDRAULIC FRACTURES

In the special case, if the hydraulic fractures are assumed to be parallel to each other we have:

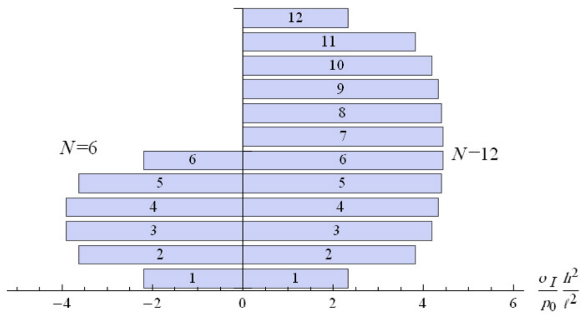


Fig. 3. The shadow stress ratio according to the location of the cracks for the six- and twelve-array cracks

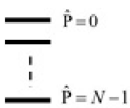
$$\frac{\sigma_I}{p_0}=\left\{1-\frac{\xi^3}{\left(1+\xi^2\right)^{\frac{3}{2}}}\right\}= \frac{3}{2\xi^2}-\frac{15}{8\xi^4}+\frac{35}{16\xi^6}-\frac{315}{128\xi^8}+O\left(\xi^{-10}\right), \qquad \xi=\frac{d}{\ell}\gg 1 \tag{2}$$

Where σ_I is shadow stress between two parallel cracks and p_0 is the internal pressure can be readily obtained by following equation [4]:

$$p_0=\frac{1}{2\pi}\frac{E'Q_0 t}{\ell^2} \tag{3}$$

According to Eq. (2), the shadow stress of adjacent cracks on one of the hydraulic fractures depends on the location of the crack and the number of parallel fractures. Therefore, to evaluate the interaction effect of N parallel hydraulic fractures on one of those in the position of $\hat{\mathrm{P}}$, the Eq. (2) with the approximation of $O\left(\varsigma^{-6}\right)$ changes as follows:

$$\begin{aligned}&\left(\frac{\sigma_I}{p_0}\right)_{\hat{\mathrm{P}}}=\frac{3\ell^2}{2d^2}\left(\mathbb{H}^2_{\hat{\mathrm{P}}}+\mathbb{H}^2_{N-\hat{\mathrm{P}}-1}\right)\\&-\frac{15\ell^4}{8d^4}\left(\mathbb{H}^4_{\hat{\mathrm{P}}}+\mathbb{H}^4_{N-\hat{\mathrm{P}}-1}\right)+O\left(\ell/d\right)^{-6},\\&\mathbb{H}_r^{(k)}=\sum_{m=1}^{m=r}\frac{1}{m^k},\\&\lim_{r\to\infty}\mathbb{H}_r^{(k)}=\mathbb{Z}\left(k\right),\ \mathrm{H}^2_{\infty}=\mathbb{Z}\left(2\right)=\frac{\pi^2}{6},\\&\mathbb{H}_0^{(k)}=0,\ \ \mathbb{H}_1^{(k)}=1\end{aligned} \tag{4}$$



Where, $\mathbb{H}_r^{(k)}$ is the generalized harmonic number of order k and $\mathbb{Z}$ is The Riemann zeta function.

Simply, the mean interaction stress‹ $\bar{\sigma}_I$ › on a crack can be obtained from the following equation without considering the position of the crack:

$$\begin{aligned}&\frac{\bar{\sigma}_I}{p_0}\approx\frac{3}{2}\left(\frac{2}{N}\right)\frac{\ell^2}{d^2}\sum_{m=1}^{N-1}\mathbb{H}^2_m-\frac{15}{8}\left(\frac{2}{N}\right)\frac{\ell^4}{d^4}\sum_{m=1}^{N-1}\mathbb{H}^4_m,\\&if\ N\to\infty\Rightarrow\frac{\bar{\sigma}_I}{p_0}\approx\frac{\pi^2\ell^2}{2d^2}-\frac{\pi^4}{24}\frac{\ell^4}{d^4}\end{aligned} \tag{5}$$

Using Eq. (4) with approximation term $O\left(\ell/h\right)^{-4}$, Fig. 3 is plotted to better understand the effect of the interaction stress, with respect to the spacing and the number of parallel cracks on each other. According to this figure, inner-fractures are further affected by shadow stress compared to outer-fractures. On the other hand, increase in the number of cracks, the interaction stress effect increases for the inner-fractures, but this increase is not significant.

According to the above-mentioned arguments, if the fluid has been injected in the array parallel hydraulic fractures with the same flow rate, the inner fractures will grow less due to the larger shadow stress.

This diversity in the growing need a modification in the calculated interaction stress, which is unused due to differences in the lengths of the cracks.

4. CONCLUSION

In this study, the pseudo traction method (PTM) is proposed to determine the evaluation of interaction stress between two oriented hydraulic cracks and is extended the array of parallel hydraulic fractures according to the number and position of cracks in the elastic medium. The present study shows that as the number of cracks increases, the interaction stress for the inner cracks increases, but this increase is not so significant for large array cracks. The inner cracks are more affected by interaction stresses (compression stress type), which will lead to a smaller growth. On the other hand, outer cracks will grow more. If the space between the inner cracks is considered more than the outer cracks, then it may lead to the simultaneous growth of cracks.

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