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Numerical Modeling of the Stability of Horizontal Multidrain Oil Wells

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ABSTRACT

The stability of the horizontal multidrain wells is a crucial issue and several factors are involved in this matter, including in-situ stresses, magnitude and distribution as well as the mainbore trajectories. In this paper, this issue is evaluated by assuming different circumstances for the above mentioned factors, based on finite difference three-dimensional modeling by using the finite difference numerical software, FLAC3D. The stability of the mainbore and lateral branches is analyzed based on the Normalized Yielded Zone Area (NYZA) criterion, i.e. the ratio of the surrounding yielded cross-sectional area to the initial area of the well. Optimum mud pressures are obtained in the mainbore and lateral branches in different mainbore trajectories under three in-situ stress regimes. In addition, the stability of the junction where the lateral branches are bifurcated from the mainbore is assessed in those situations. The optimum trajectory of the mainbore, in which the junction has obtained the most stable condition, is selected in each stress regime. It was concluded that in the Normal Faulting (NF) stress regime, the mainbore and junction stability varies in relation to the mainbore trajectories, inversely. However, in the other two stress regimes, i.e. Strike Slip (SS) and Reverse Faulting (RF), the variations of the mainbore and junction stability are in the same trend with respect to the mainbore trajectory deviations.

Key words: *multidrain wells*; *in-situ stresses*; *NYZA*; *mainbore*; *lateral branches*

1. Introduction

Multidrain wells consist of a main wellbore and several lateral branches. These lateral branches could be located in one or more planes along with the main wellbore. They enhance the drainage geometry of the reservoir, reduce the coning phenomenon and ameliorate the production of oil (Garrouch *et al.*, 2004).

Horizontal wells are becoming the norm rather than the exception where they can present advantages over conventional wells: increased productivity, accelerated recovery and reduced coning tendencies. However, they are already, and will be more and more, replaced by “advanced wells” in those situations. The term “advanced wells” refers to wells that have complex geometries and architecture. The most common are cluster wells (slanted or curved branches drilled with different azimuths from the same vertical hole), stacked wells, multilateral wells (composed of several horizontal arms drilled from the same horizontal drains), reentry wells, and 3D wells (Gadelle and Renard, 1999). Fig. 1 shows various types of the advanced multidrain wells and their application according to the specific reservoir.

Using multi-branch horizontal wells to enhance oil recovery has been applied widely all over the world, and it is necessary for low permeability reservoirs development (Yin *et al.*, 2010). Multilateral

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wellbores – separate drain holes or branches, drilled from a single primary borehole (Fraija *et al.*, 2002) – offer the potential for substantial improvement in well economics (Vij *et al.*, 1998). They potentially reduce total capital expenditures and development costs as well as operational expenses by decreasing the number of the required wells (Jordan *et al.*, 2002). This technology can help us to produce multiple reservoirs, enhance drainage pattern, increase fracture exposure, reduce environmental damage, reduce overburden and surface facilities costs, decrease impacts of water/gas coning, etc. (Vij *et al.*, 1998; Garrouch *et al.*, 2004). The current costs of drilling and completion of multidrain wells are more than several million dollars for each branch (Garrouch *et al.*, 2004). Therefore, a suitable design for optimum production of these wellbores is crucial.

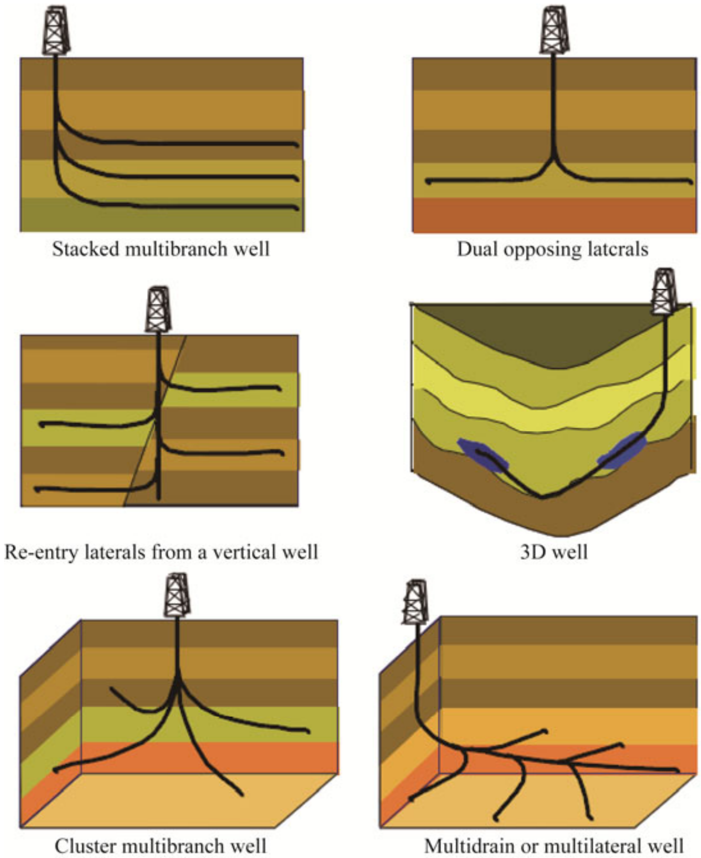

Fig. 1. Various types of advanced wells (Gadelle and Renard, 1999).

Drilling and production problems often result from mechanical failure of wellbores. Mechanical stability of the wellbore depends on the magnitude and orientation of in-situ stresses, rock strength, fluid in the wellbore and those contained in formation, and the orientation of the wellbore. Collapse of the junction is the major cause of multilateral failure (Manriquez and Podio, 2008). In multidrain wells, the stability of junction is essential for efficient and effective production (Soliman and Boonen, 2000).

In-situ stresses concentrate around the wellbore after it is bored. This concentration would lead to the failure of the surrounding rock mass contingent upon its strength. The drilling engineers alleviate the stress concentration using mud pressure and optimization of wellbore orientation in accordance with the principal in-situ stresses. In general, variation of wellbore inclination is restricted and thus the stability should be controlled by means of suitable mud pressure employment (Al-Ajmi, 2006).

The most conventional and simplest model for wellbore stability analysis is linearly elastic. The important advantage of linear elastic model employment is its limited number of parameters to be defined (Soliman and Boonen, 2000). However, elastoplastic model gives more realistic results for mechanical stability. It is because this model simulates the behavior of medium after reaching the critical stress level. In other words, going over the critical stress limit in this case does not mean that the rock mass has completely failed, separated or collapsed. In contrast, it means that the medium is capable of absorbing more stresses and accepting more deformation (Hawkes *et al.*, 2002).

Brister (1998) presented a review of the problems encountered in the drilling and completion of a multilateral well in East Wilmington field in California, where, junction instability was substantial among the existing problems. Thus, pointing out and studying stability behavior of junctions in different multilateral scenarios becomes a very important issue in planning and design.

When two holes interact, the interference (disturbance) that a lateral hole causes on the stresses around the mainbore is particularly interesting. However, information about research conducted in a multilateral scenario where two holes interact, is limited. Aadnøy and Edland (1999) and Aadnøy and Froitland (1991) investigated the effect of wellbore geometry on the stability of multilateral junctions using the elasticity theory. Fuentes *et al.* (1999) presented a field case of a stability analysis of a multilateral well in a sand formation for a particular field. Goshtasbi *et al.* (2013) investigated the effect of various lateral well trajectories on the stability of the junction in a vertical oil well with one branch, under seven different stress regimes. They obtained the optimum trajectories of lateral wellbore, in which the junction has reached the lowest mud pressure, in each stress regime.

In this paper an attempt is made to analyze the stability of a horizontal multidrain oil well by using a three-dimensional finite difference code, FLAC3D, which has been developed for implementation of mechanical calculations in the engineering problems (Itasca, 2006). Actually, the mainbore and its branches are located in a horizontal plane. The effect of various trajectories was determined on the stability of the junction, the mainbore and the lateral branches in horizontal direction. In addition, the variation of plastic zone in relation to mud pressure in the mainbore and lateral branches was obtained. To assess the mainbore and lateral branches instability problems, the Normalized Yielded Zone Area (NYZA) criterion, i.e. cross-sectional area of plastic zone division by the original area of the wellbore, is used in the simulation. It has been shown that the value of NYZA larger than one leads to wellbore instability (Salehi *et al.*, 2010). The criterion was incorporated in an FISH program and was implemented in FLAC3D software to analyze the wellbore stability and the variation of plastic zone in relation to mud pressure was obtained in the mainbore and lateral branches.

2. Stresses Around Deviated Boreholes

Stress-strain transformation matrix was used to involve the effect of the deviated wellbore azimuth in the calculations. Fig. 2 illustrates the geometry of a general inclined wellbore. In-situ stresses, σ_H, σ_h and σ_V assumed to be directed in x', y', and z' global coordinate. The stresses around the wellbore are more conveniently described by a local coordinate frame *x, y, z* with the *z*-axis being parallel to the wellbore axis. The *x*-axis is chosen to be parallel to the lower-most radial direction of the wellbore, and the *y*-axis to be horizontal.

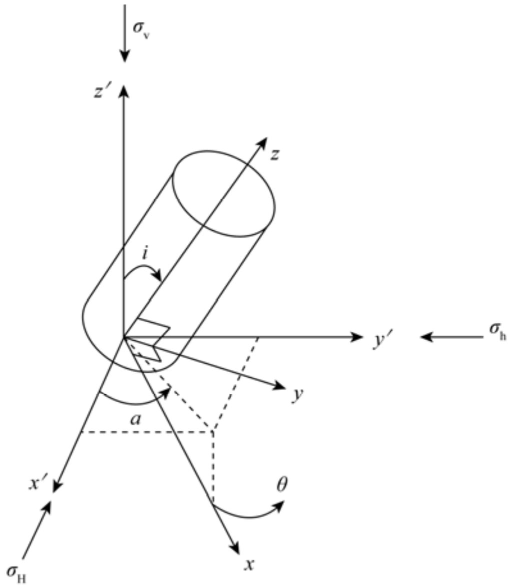

Fig. 2. Stress transformation system for the deviated borehole (Fjær *et al.*, 1992).

A stress transformation from the global coordinate frame to the local coordinate frame, which is described mathematically by use of the direction cosines is as follows (Fjær *et al.*, 1992):

$$\boldsymbol{\sigma}^0 = \boldsymbol{l}\boldsymbol{\sigma}'\boldsymbol{l}^{\mathrm{T}}; \tag{1}$$

$$\boldsymbol{l} = \begin{bmatrix} \cos a \cos i & \sin a \cos i & -\sin i \\ -\sin a & \cos a & 0 \\ \cos a \sin i & \sin a \sin i & \cos i \end{bmatrix}; \tag{2}$$

$$\boldsymbol{\sigma}' = \begin{bmatrix} \sigma_H & 0 & 0 \\ 0 & \sigma_h & 0 \\ 0 & 0 & \sigma_V \end{bmatrix}, \tag{3}$$

where a is the azimuth of the wellbore, which is measured counterclockwise from the projection of the wellbore axis on the horizontal plane and the direction of the maximum horizontal in-situ stress, i is the wellbore inclination or wellbore deviation, which is measured clockwise from the wellbore axis and the vertical direction, $\boldsymbol{l}$ is the direction cosines matrix, $\boldsymbol{\sigma}'$ is the in-situ stress tensor, and $\boldsymbol{\sigma}^0$ is the stress tensor from the global frame to the local frame.

With the stress transformation equation, the original formation stresses expressed in the (x, y, z) coordinate system become

$$\boldsymbol{\sigma}^0 = \begin{bmatrix} \sigma_{xx}^0 & \tau_{xy}^0 & t_{xz}^0 \\ \tau_{yz}^0 & \sigma_{yy}^0 & \tau_{yx}^0 \\ \tau_{zx}^0 & \tau_{zy}^0 & \sigma_{zz}^0 \end{bmatrix}. \tag{4}$$

The superscript "0" on the stresses denotes that these are the original formation stresses. By substituting $i = \pi/2$ into Eq. (4), the amount of stresses can be estimated at the horizontal wellbore wall.

3. In-Situ Stresses and Rock Characterization

Stability of the multidrain horizontal wells is considered in three possible stress regimes, i.e. normal faulting (NF), strike slip (SS), and reverse faulting (RF), as shown in Table 1.

Table 1 In-situ stress regimes (Al-Ajmi, 2006)

Stress regime	σ_V (psi/ft)	σ_H (psi/ft)	σ_h (psi/ft)
NF	1.00	0.86	0.76
SS	0.89	1.00	0.85
RF	0.89	1.10	0.98

As the actual field data, the horizontal multidrain stability analysis has been conducted in a well from one of the Iranian oilfields. Desired formation is assumed existing at a depth of 8000 ft where pore pressure is equal to 0.45 psi/ft. The formation has cohesion of 2.5 MPa, elastic module of 15 GPa, Poisson's ratio of 0.22, tensile strength of 2.9 MPa, and a friction angle of 30°.

4. Stability Analysis by Using Numerical Modeling

The model consists of a mainbore and two lateral wells in the horizontal plane. The mainbore and lateral wells have a 16 cm radius. Both lateral wells are constructed with a 30° deviation from the mainbore. Fig. 3 illustrates the general meshed scheme of the model in three dimensions along with boundary conditions. To unify the meshing of the system, model boundaries are taken into account to be parallel with the related opposite wells. The angle between the horizontal mainbore and the horizontal in-situ stresses varies from 0° to 90° with a 15° interval. Generally, 147 plots are obtained considering the number of assumed orientations for the mainbore, three different stress regimes and six different mud pressures are used to record the variation of NYZA in each model. Stability of the mainbore and lateral branches has been evaluated under different mud pressure conditions. Optimum mud pressure is obtained for various circumstances of the mainbore orientations and in-situ stress regimes. Since the Mohr–Coulomb criterion is the most common criterion in the stability analysis of the underground openings, the rock mass behavior is considered as a Mohr–Coulomb material around the well. Actually, two main effective factors including mainbore inclination and in-situ stress regime variations are considered in the well stability.

As the distance from the junction increases, the effect of wells intersection gradually decreases and eventually the interaction between the mainbore and lateral wellbores will disappear. Once the interaction between the mainbore and lateral wellbores was finished, both mainbore and lateral branches were treated as two single wells. Thus, mud pressures can be determined in these wells by using the existing stability criteria for a single wellbore. In each model, the variation of NYZA was calculated in the mainbore and lateral branches in different internal (mud) pressures. The variation of NYZA with over balance mud pressure is shown in Fig. 4 for the mainbore drilled in the SS stress regime, with a direction of 60° from the maximum horizontal stress, σ_H. In different situations of stresses and pressures, the optimum mud pressure where NYZA is equal to one was determined by interpolation of the obtained datasets by use of MATLAB software.

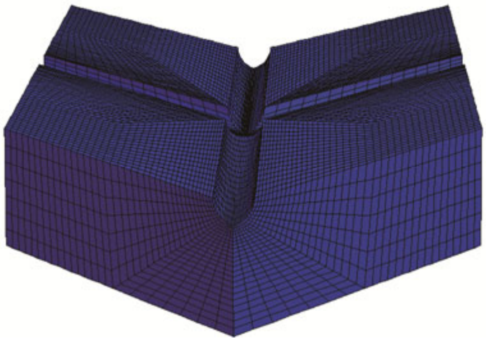

Fig. 3. General scheme of a horizontal multidrain well in FLAC3D.

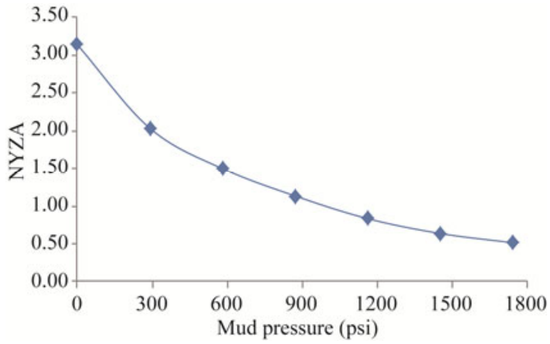

Fig. 4. Variation of NYZA with mud pressure in the mainbore at 60° to the maximum horizontal stress in SS stress regime.

This research only investigates the mud pressure required to avoid shear failure at the junction, mainbore and lateral branches (i.e., collapse pressure), while the fracture pressure is not investigated. Unlike the fracture pressure, the collapse pressure will not exceed the minimum in situ stress and thus the numerical code will carry out the solution process for the mud pressure range from the pore pressure to the minimum of in situ stress.

By considering the mud pressure required to avoid collapse failure, it can be observed that NYZA decreases when the well mud pressure increases. Consequently, by increasing the mud pressure, the well wall will be stabilized, significantly.

When the optimum mud pressure was obtained in every situation, plots of the optimum mud pressure can be illustrated as the function of the mainbore inclination and stress regimes. Consequently, the direction at which the optimum mud pressure has the least amount is selected as the optimum trajectory of the single well. It should be noted that the optimum pressure is the minimum pressure to stabilize the well and lower levels of pressure make instability in the well very likely. Except for the mentioned stress regimes, we considered a NF–SS stress regime, in which $\sigma_V = \sigma_H \geq \sigma_h$. Results show that when the single well is drilled along one of the horizontal stresses, two conditions are expected for the extension of the plastic zone:

(1) In the case of equality of other two stresses perpendicular to the well axis, the plastic zone will be axisymmetric around the well.

(2) In the case of inequality of other two stresses perpendicular to the well axis, the plastic zone will be roughly elliptic around the well. In this case, displacement magnitude and plastic zone

extension will be maximized in the minimum stress direction, and then the failure of the well wall starts from this direction. Thus, during the installation of casing in the well, extreme measures should be taken in this direction to prevent future problems. The difference between displacements and radius of the plastic zone increases as the difference between two in-situ stresses perpendicular to the well axis increases.

4.1 Stability Analysis of A Single Well

The collapse pressure depends on the magnitudes, directions and mutual relationships of the in situ stresses. In multidrain wells, the inclination\azimuth of the mainbore and lateral branches with respect to in-situ stresses trajectory are different. Thus, because of various deviations of these wells with respect to the in-situ stresses, the required mud pressures are different for the mainbore and lateral branches. In this section, the stability analysis of the mainbore, right-handed branch, and left-handed branch is presented in different situations of stress regimes and mainbore trajectories.

4.1.1 *NF Stress Regime*

Fig. 5 shows the variation of the optimum mud pressure of a single horizontal well (mainbore, right-handed branch, and left-handed branch) with respect to the mainbore azimuth which is measured from the direction of σ_H.

It can be observed that, when the mainbore is declined from the direction of σ_H, the mud pressure decreases. However, the situations in the lateral wells are different. The maximum mud pressures for the right-handed and left-handed wells are at 0° and 30° in relation to σ_H, respectively. It means that in the NF stress regime, by increasing a single well deviation (either mainbore or lateral wells) from the σ_H direction, the required mud pressure decreases. Therefore, under the condition of the drilled horizontal wells, the direction of the minimum horizontal stress σ_h is the most stable well and the most unstable well is located in the direction of σ_H.

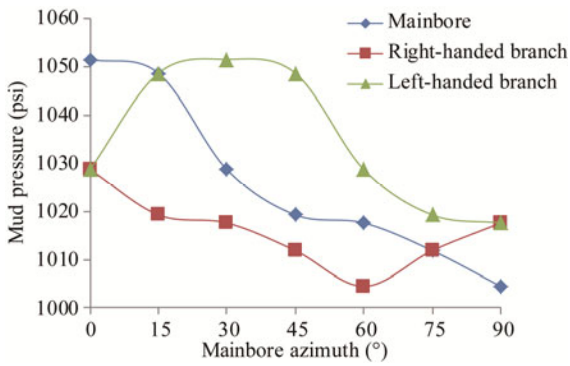

Fig. 5. Minimum overbalance pressures of mainbore, right-handed and left-handed branches as a function of mainbore azimuth in NF stress regime.

In all situations where the mainbore was drilled in the directions other than the directions of the horizontal stresses, the mud pressure required for drilling the left-handed well is more than required for the right-handed one. However, in cases when the mainbore was drilled in the direction of the horizontal stresses, the required mud pressures are the same for two lateral wells because of the same deviations of this well with respect to the horizontal stresses.

4.1.2 *SS Stress Regime*

At this stress regime unlike the NF stress regime, the maximum mud pressure of the mainbore is related to the drilling in the direction of σ_h and the minimum mud pressure is related to 15° deviation with respect to σ_H, as shown in Fig. 6.

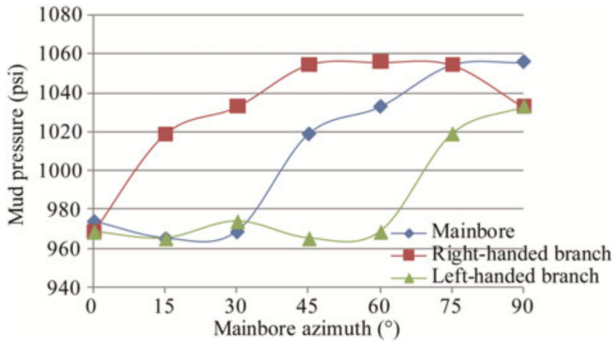

Fig. 6. Minimum overbalance pressures of mainbore, right-handed and left-handed branches as a function of the mainbore azimuth in SS stress regime.

It can be determined that in all azimuths of the mainbore except for 0° and 90°, where the lateral mud pressure is the same, the left-handed branch mud pressure is smaller than the right-handed one. As shown in Fig. 6, the left-handed branch has two minimum mud pressures at the mainbore azimuths of 15° and 45° (i.e. the branch direction in σ_H direction).

4.1.3 *RF Stress Regime*

At this stress regime, the drilled mainbore in the direction of σ_H shows the minimum amount of mud pressure, as shown in Fig. 7.

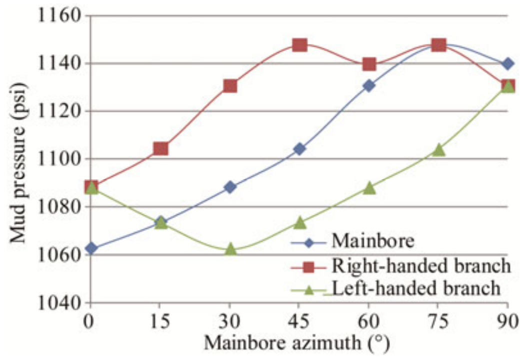

Fig. 7. Minimum overbalance pressures of mainbore, right-handed and left-handed branches as the function of the mainbore azimuth in RF stress regime.

It can be found that the mainbore, which was drilled in the direction of σ_H, needs the lowest mud pressure. By increasing the well inclination from σ_H direction well stability decreases significantly, until 75° which reaches its maximum level of the mud pressure; then decreases in the direction of σ_h. The right-handed well shows the maximum pressure at two directions of the mainbore, i.e. 45° and 75° from σ_H direction. The minimum mud pressure for the left-handed well is related to the mainbore deviation of 30° with respect to σ_H. In this stress regime, at the mainbore directions except for the horizontal stresses, the left-handed branch mud pressure is smaller than the right-handed one as well as SS stress regime.

4.2 Analysis of Junction Stability

The junction or the place where the lateral wells are bifurcated from the mainbore is the most crucial part of multidrain wells. The minimum required mud pressure for the stability of a wellbore junction is larger than that of the main or lateral branches in different stress regimes. The junction instability caused by the instability of both the mainbore and lateral wells and instability of the lateral wells depends on the inclination\azimuth with respect to in-situ stresses trajectory. Thus, the junction stability varies with different lateral well trajectories because of various deviations of lateral wells with respect to in-situ stresses. In this section, the stability analysis of the junction for horizontal multidrain wells is presented in different situations of stress regimes and the mainbore trajectories.

4.2.1 *NF Stress Regime*

Fig. 8 demonstrates displacement magnitudes in the junction area with respect to the mainbore azimuths under NF stress regime.

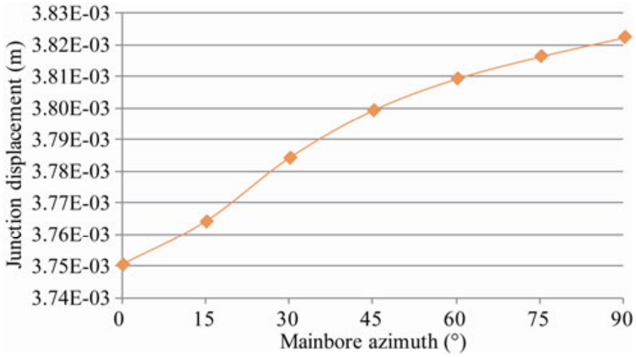

Fig. 8. Junction displacements as the function of the mainbore azimuth in NF stress regime in the horizontal multidrain well.

It can be found that the maximum displacement occurs at the mainbore direction of the minimum horizontal stress σ_h. However, as mentioned above, the most stable direction for the mainbore drilling is located in this direction.

Displacement contours of the horizontal multidrain well in the NF stress regime are shown in Figs. 9 and 10 for the drilling of the mainbore in σ_H and σ_h directions, respectively. It can be concluded that the junction is the most unstable part of the multidrain wells.

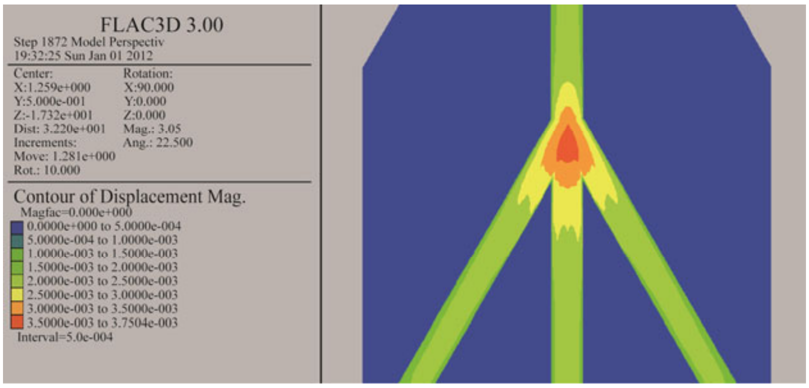

Fig. 9. Displacement contour of a horizontal multidrain in NF stress regime and under no mud pressure for the mainbore along the direction of σ_H .

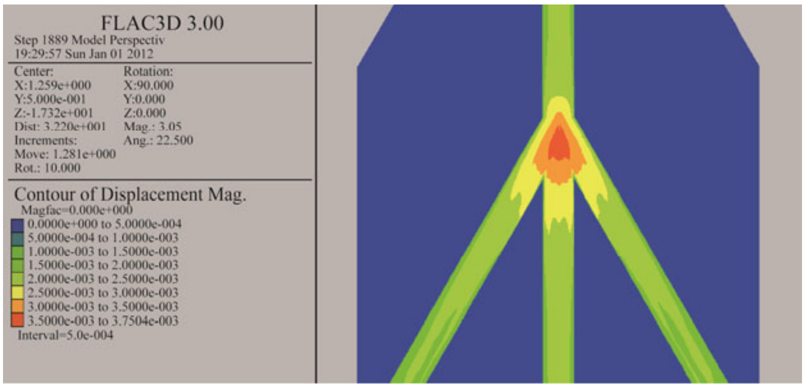

Fig. 10. Displacement contour of a horizontal multidrain in NF stress regime and under no mud pressure for the mainbore along the direction of σ_h .

4.2.2 *SS Stress Regime*

At this stress regime, a large difference can be observed between junction displacements when the mainbore is drilled at the azimuth of 0° to 75° with respect to azimuth of 90°, as shown in Fig. 11.

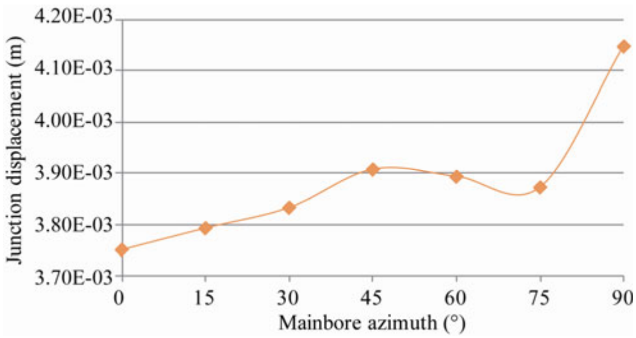

Fig. 11. Junction displacements as a function of the mainbore azimuth in SS stress regime.

As in SS stress regime, the minimum and the maximum instabilities of the junction are related to the mainbore directions of σ_H and σ_h, respectively. Thus according to the obtained results from the mainbore and junction stability analysis in SS stress regime, it can be concluded that drilling the mainbore in the direction of σ_h is the most unstable trajectory for both mainbore and junction.

Displacement contours of the horizontal multidrain well in the SS stress regime are shown in Figs. 12 and 13 for the drilling of the mainbore in σ_H and σ_h directions, respectively.

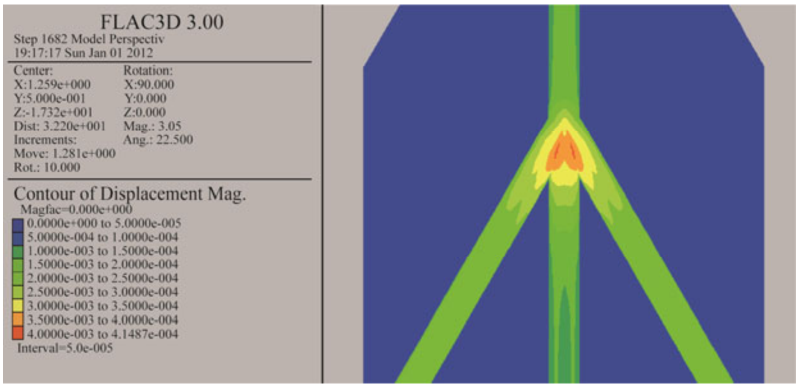

Fig. 12. Displacement contour of a horizontal multidrain in SS stress regime and under no mud pressure for the mainbore along the direction of σ_H .

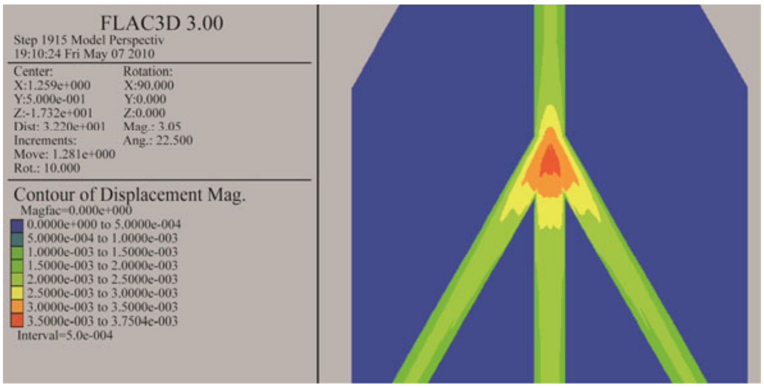

Fig. 13. Displacement contour of a horizontal multidrain in SS stress regime and under no mud pressure for the mainbore along the direction of σ_h .

4.2.3 *RF Stress Regime*

As shown in Fig. 14, the minimum and the maximum displacements in the junction are related to the mainbore directions of 90° and 60°, respectively. It means that when the left-handed branch is drilled in the direction of the minimum horizontal stress, the most case of instability will occur at the junction.

Displacement contours of the horizontal multidrain well in the RF stress regime are shown in Figs. 15 and 16 for the drilling of the mainbore in σ_H and σ_h directions, respectively. It can be understood that the junction in the mainbore direction of σ_h is more instable than that in the direction of σ_H .

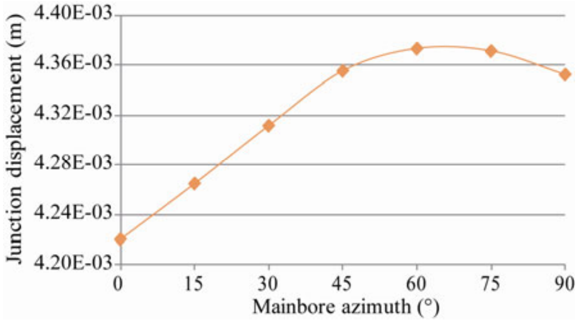

Fig. 14. Junction displacements as the function of the mainbore azimuth in RF stress regime.

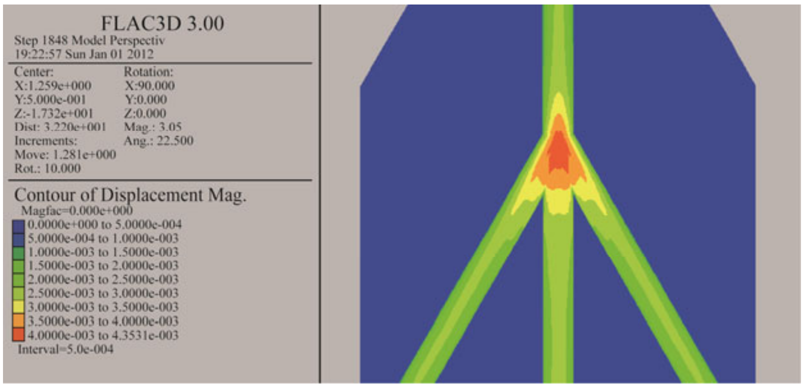

Fig. 15. Displacement contour of the horizontal multidrain in RF stress regime and under no mud pressure for the mainbore along the direction of σ_H.

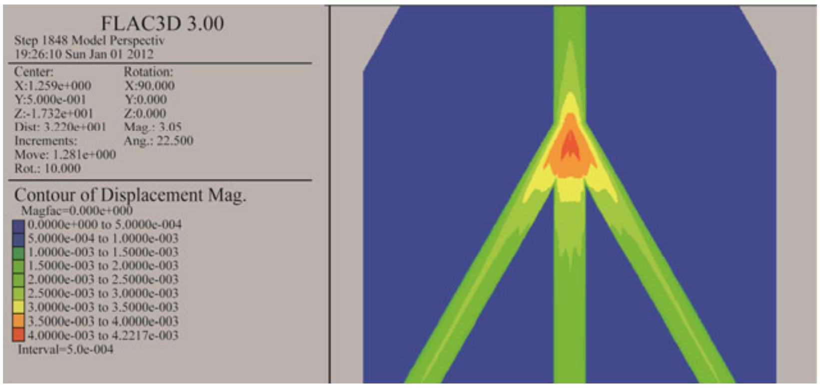

Fig. 16. Displacement contour of the horizontal multidrain in RF stress regime and under no mud pressure for the mainbore along the direction of σ_h.

5. Conclusions

Stability analysis of a horizontal multidrain well was presented under three stress regimes and different mainbore trajectories. It was determined that, in each stress regime, the minimum required mud pressure for stability of the well is larger in the junction area than that of the mainbore or lateral branches. In other words, the junction region is the most crucial part of multidrain wells. Therefore, according to the numerical modeling, it is strongly recommended that a mud weight close to the horizontal in-situ stress should be used in the formation during drilling.

It was obtained that, in situations where the well is drilled in the direction of a principal stress, in case of equality of other two principal stresses, the plastic zone and displacement are distributed symmetrically around the wellbore. Otherwise, the displacements and instabilities will increase in the direction of the minimum principal stress. An increase in the σ_H/σ_h ratio makes the optimum trajectory approach σ_H direction.

In stress regimes of NF, SS and RF, the most stable trajectories of the single well are located in σ_h, 15° from σ_H, and σ_H directions, respectively. At NF stress regime, in the mainbore directions except for horizontal stresses, the right-handed well mud pressure was smaller than that of the left-handed one. However, at the other two stress regimes, i.e. RF and SS, the results were vice versa. At all stress regimes in the case of drilling, the mainbore in horizontal stresses directions, the amount of the mud pressures of right-handed and left-handed were exactly similar.

Even though, drilling of the mainbore in the direction of σ_h in NF stress regime was the most stable but the junction was most unstable in relation to other mainbore trajectories. It was determined that the most stable case for the junction was the direction of σ_H for drilling of the mainbore.

It was concluded that, excluding the NF stress regime in which the variation of the mainbore and junction stability in relation to the mainbore azimuth are inverse, and in other two stress regimes, the trends of stability variations in the mainbore and junction are approximately similar.

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