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ORIGINAL PAPER

3D numerical stability analysis of multi-lateral well junctions

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Abstract The most important factors in multi-lateral well stability analysis are the magnitude of in situ stresses, the relation between the amount of in situ stresses and orientation of lateral wellbore. In this research, the stability analysis of multi-lateral junction is carried out using FLAC3D numerical code by considering seven varied stress regimes and different lateral wellbore orientations. The Normalized Yielded Zone Area (NYZA, ratio of surrounding yielded cross-sectional area to initial area of well) is determined for different junction mud pressures as well as diverse orientations of lateral wellbore. Then, the junction optimum mud pressure of each lateral wellbore orientation is calculated; hence, the optimum trajectory of lateral wellbore, in which the junction has got the lowest optimum mud pressure, is selected in each stress regime. The stability analysis of multi-lateral wells by means of finite difference method shows that in each stress regime the required mud pressure for the stability of junction is much more than that of the lateral branch and the main wellbore.

Keywords Multi-lateral well · NYZA · Optimum pressure · Optimum trajectory · Junction

Introduction

Multi-lateral wells consist of a main wellbore and several lateral branches. These lateral branches could be located in one or more plane along with the main wellbore. The multi-lateral wells are generally used for heavy oil reservoirs and reservoirs with complex geology, such as isolated pockets, layered reservoir and faulted reservoir. Multi-lateral wells enhance the drainage geometry of the reservoir, reduce the coning phenomenon and ameliorate the production of oil (Garrouch et al. 2004).

The multi-lateral wells require additional initial investment in equipment, but potentially reduce total capital expenditures and development costs as well as operational expenses by decreasing the number of required wells (Jordan et al. 2002). The current costs of drilling and completion of multi-lateral 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.

The stability of wellbore is controlled by the in situ stress regime. These stresses concentrate around the wellbore after it is bored. This concentration would lead to 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). In multi-lateral wells, the stability of junction is essential for efficient and effective production (Soliman and Boonen 2000).

Recently, in the North Sea several multi-lateral wells have encountered stability problems. For example, in a wellbore the casing of a branch is deformed into the main wellbore and caused not only stability problem but also production difficulty (Soliman and Boonen 2000).

The most conventional and simplest model for wellbore stability analysis is linear 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

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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 (McLellan and Hawkes 2002).

In this research, the criterion for assessing the wellbore instability is based on the development of yielded (plastic) area. The criterion which is often used for indication of well-bore instability risk is the Normalized Yielded Zone Area (NYZA), which is dividing the cross-sectional area of plastic zone to original area of the wellbore. From the experience gained, the instability often occurs when the amount of NYZA is more than one (McLellan and Hawkes 2002).

Furthermore, the FLAC3D numerical code is utilized to carry out the stability analyses. This software is a three dimensional finite difference code which is developed for implementation of mechanical calculations in the engineering problems. This numerical code simulates the behavior of soil, rock and other media which have a plastic behavior at the time of yielding (FLAC3D 2006). The variation of plastic zone with respect to the variation of mud pressure in junction is determinable by the aid of this numerical code.

Geomechanical parameters and in situ stress regimes

The in situ stress regimes considered in the analysis of junction are hydrostatic, normal faulting (NF), strike-slip faulting (SS), normal-strike slip faulting (NF–SS), reverse faulting (RF) and reverse-strike slip faulting (RF–SS). In Table 1, the relative magnitude of in situ stresses in the above mentioned stress regimes is summarized.

The seven in situ stresses used in this research study, extracted from Zhang et al. 2006 and Al-Ajmi 2006, are given in Table 2. Also, the geomechanical parameters used in numerical analysis are presented in Table 3, extracted from Zhang et al. 2006.

Table 1 In situ stress regimes

Stress regime	Relative magnitude of the stresses
Hydrostatic	$\sigma_v = \sigma_H = \sigma_h$
NF	$\sigma_v > \sigma_H > \sigma_h$
NF with isotropic horizontal stresses	$\sigma_v > \sigma_H = \sigma_h$
SS	$\sigma_H > \sigma_v > \sigma_h$
NF–SS	$\sigma_v = \sigma_H > \sigma_h$
RF	$\sigma_H > \sigma_h > \sigma_v$
SS–RF	$\sigma_H > \sigma_v = \sigma_h$

Table 2 Seven in situ stress regimes used in modeling

Stress regime	Vertical stress σ_v (MPa)	Maximum horizontal stress σ_H (MPa)	Minimum horizontal stress σ_h (MPa)	Pore pressure (MPa)
Hydrostatic	54	54	54	24.8
NF	69.0	55.2	48.3	31.7
NF with isotropic horizontal stresses	58.8	44.1	44.1	26.5
SS	41.4	50.5	36	18.6
NF–SS	44.6	44.6	36.3	23.7
RF	49.1	60.7	54.0	24.8
SS–RF	49.1	60.7	49.6	24.8

Numerical analysis of multi-lateral junctions

3D numerical models

In this research study, the dimensions of the generated models for multi-lateral wells, using FLAC3D numerical code, are 600×200×800 cm (Fig. 1). In all models, the main (vertical) and lateral wellbores are 32 cm in diameter. In Fig. 1, the range of inclination and direction variation for the lateral wellbore is shown.

The failure criterion assumed in these analyses is the Mohr–Coulomb, and the in situ stress regimes considered are stated in Table 2. Furthermore, the modeled lateral well-bores have got an angle of 0°, 15°, 30°, 45° and 60° relative to the horizontal line (i) and the directions of 0°, 30°, 60° and 90° relative to the maximum horizontal stress (α). In fact, with respect to the three factors of inclination, direction of lateral wellbore and in situ stress regime, the optimum mud pressure in the junction is determined. In the aggregate, 840 models are generated to conduct this research, considering the number of assumed orientations for the lateral wellbore and different stress regimes, and knowing that six diverse mud pressures are used to record the variation of NYZA in each model.

Table 3 Rock mass geomechanical parameters

Parameter	Dimension	Quantity
Tensile strength (T)	MPa	1.5
Cohesion (C)	MPa	1.3
Internal friction angle (φ)	Degree	30
Bulk modulus (K)	GPa	11.0
Shear modulus (G)	GPa	8.7
Young's modulus (E)	GPa	20.6
Poisson's ratio (υ)	–	0.189

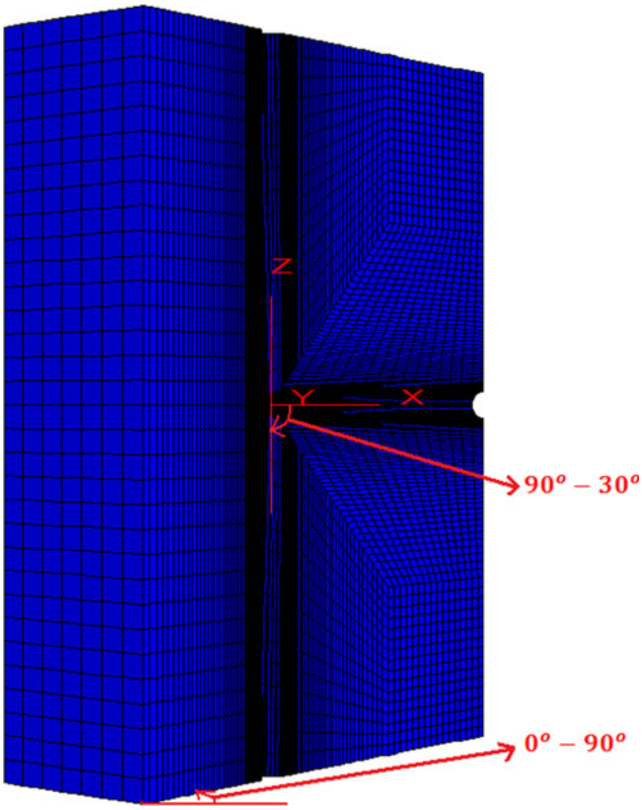

Fig. 1 General scheme of the generated models

Stability analysis of the junction

In Fig. 2, the modeled junction along with the plastic zone surrounding the wellbores is shown in a two dimensional view. The plastic zones are illustrated with non-blue colors, and the blue regions are not in the plastic phase. Most instabilities in multi-lateral wells occur in the regions shown in Fig. 2 (V_1, V_2, V_3 and V_4). In the FLAC3D code, the volume of a specific region is merely determined by calculation of zones volume. Also, the instability of the junction is due to both main and lateral wellbores instability. Hence, to determine the NYZA in the junction, it is necessary to consider some equivalent regions which take into account both main and lateral wellbores (Fig. 2).

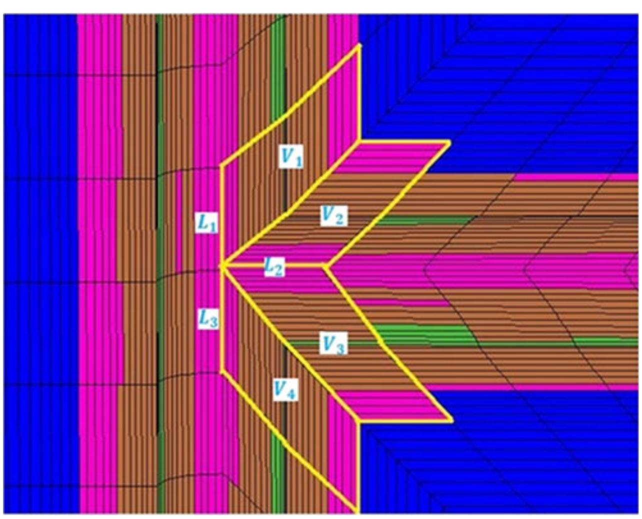

Fig. 2 General scheme of the junction and the surrounding plastic zone

Formula 1 can be used to calculate the junction NYZA with respect to Fig. 2.

$$NYZA = 2\left[\left(\frac{V_1}{L_1\pi r^2}\right) + \left(\frac{V_2}{L_2\pi r^2}\right) + \left(\frac{V_3}{L_2\pi r^2}\right) + \left(\frac{V_4}{L_3\pi r^2}\right)\right] \quad (1)$$

With this regard, V_1, V_4 and V_2, V_3 are the volumes of plastic zones at junction related to the vertical and lateral wellbores, respectively. $L_1\pi r^2$, $L_3\pi r^2$ and $L_2\pi r^2$ are the volumes of the vertical and lateral wellbores (with the highest plastic zone around them) at junction, respectively, and r is the radius of both main (vertical) and lateral wellbore, which is 16 cm. Hence, the NYZA is the volume of the plastic zone divided by the volume of the wellbores at the junction. In this research study, the junction NYZA is calculated using FISH programming language, which is embedded in FLAC3D code.

The junction optimum mud pressure (the minimum mud pressure needed for junction stability) is the pressure in which the NYZA is equal to one. Therefore, in each model the variation of NYZA in different junction mud pressures (six varied levels) is calculated, and then the best curve is fitted to the resulted points, employing MATLAB software. As a result, the optimum mud pressure is accurately determined using the curve formula. For example, in Fig. 3 the variation of NYZA versus junction overbalance mud pressure (junction mud pressure minus pore pressure) is illustrated for a particular lateral well orientation and stress regime.

As mentioned, with the increase in mud pressure, both NYZA and displacement reduce, and thus the junction gets more stable. At the beginning, both NYZA and displacement decrease with a high rate, but gradually a lower rate of reduction is seen. Figures 3 and 4 show the variation of NYZA and

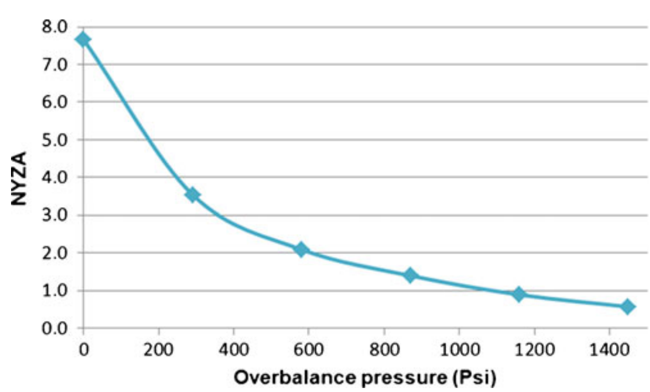

Fig. 3 Variation of NYZA in junction for a branch with the inclination of 60° and the direction along σ_H in hydrostatic stress regime

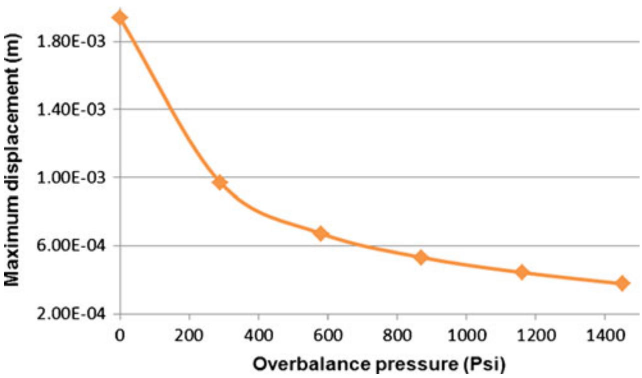

Fig. 4 Variation of maximum displacement in junction for a branch with the inclination of 60° and the direction along σ_H in hydrostatic stress regime

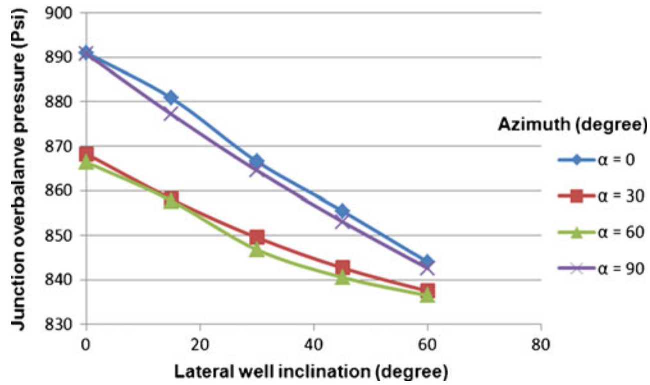

Fig. 6 Minimum overbalance pressure as a function of lateral wellbore trajectory in NF stress regime with isotropic horizontal stress

displacement versus overbalance pressure, respectively, for a junction with lateral wellbore drilled in a 60° inclination and the direction along σ_H under the hydrostatic stress regime.

Having the optimum pressure in each case, it becomes possible to plot the graphs which show the minimum junction overbalance pressure in different lateral well orientations and for a specific stress regime (Figs. 5, 6, 7, 8, 9, 10 and 11). Then, the optimum trajectory of lateral well, the orientation with the lowest junction overbalance pressure, is determined by means of these plots. In Fig. 8, for instance, a lateral drilling with an inclination of 15° and a direction along the maximum horizontal stress has the optimum lateral well orientation in the SS stress regime. It should be noted that the junction optimum pressure is the minimum pressure to stabilize the junction, and lower levels of pressure make instability in the junction very likely.

Wellbore stability analysis in varied stress regimes

In the following, the junction optimum mud pressure in different orientations of lateral well and diverse in situ stress regimes is determined. In all figures shown in this research, the meaning of minimum overbalance pressure is the optimum mud pressure minus the pore pressure.

- In hydrostatic stress regime, by increasing the lateral wellbore inclination, the instability of the junction increases. Furthermore, the junction mud pressures are not significantly varied in diverse directions of lateral wellbore. In this stress regime, the lowest junction mud pressure is for the horizontal lateral wells with directions other than σ_H andσ_h . In addition, the highest one is for the lateral wells with the maximum inclination (60° in this case) and the directions along σ_H or σ_h (Fig. 5).
- Most of the facts mentioned above are also true about the NF stress regime with isotropic horizontal stresses. However, in contrast to hydrostatic regime, in this stress regime by the increase of lateral wellbore inclination, the stability of the junction increases. Also, in the case that the lateral wellbore is 60° oblique and has an angle of 30° and 60° from σ_H or σ_h, the junction mud pressure is in its minimum level (Fig. 6).
- In NF stress regime, when the lateral wellbore is in directions other than σ_h, the increase of inclination angle would lead to less required mud pressure. Consequently,

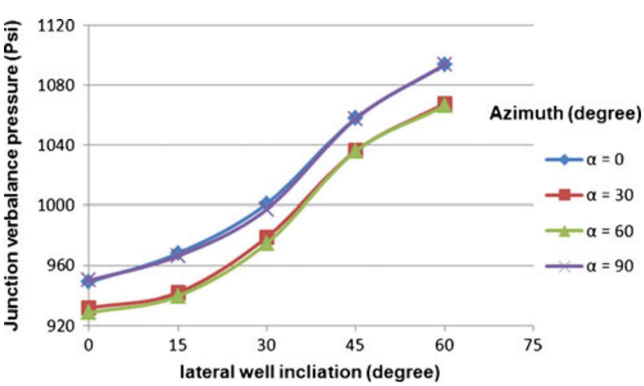

Fig. 5 Minimum overbalance pressure as a function of lateral wellbore trajectory in hydrostatic stress regime

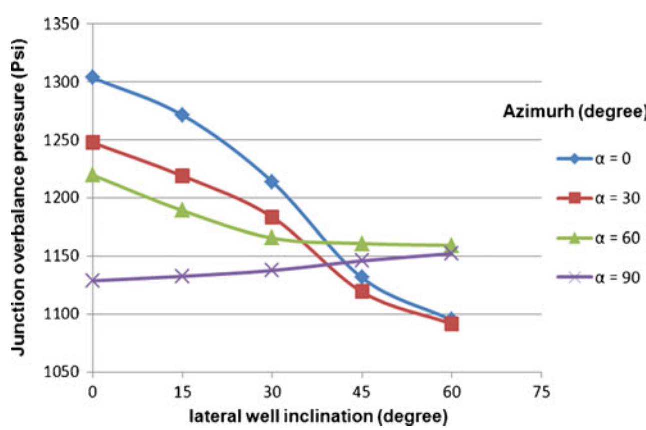

Fig. 7 Minimum overbalance pressure as a function of lateral wellbore trajectory in NF stress regime

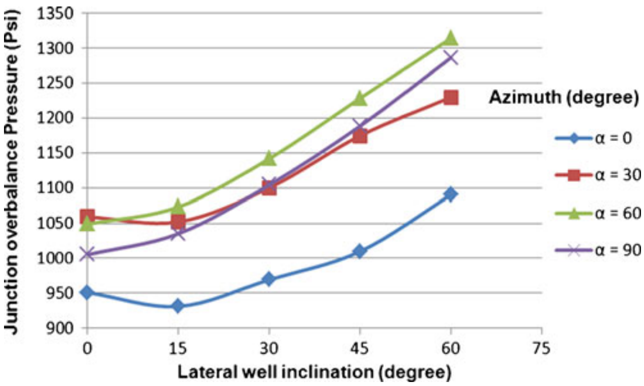

Fig. 8 Minimum overbalance pressure as a function of borehole trajectory in SS stress regime

the maximum junction mud pressure corresponds to the horizontal lateral well with direction parallel to σ_H.

- Generally, in SS stress regime, the increase of lateral wellbore inclination angle leads to more unstable junction. In this stress regime, regarding each individual inclination, the junction mud pressure for lateral wellbores with directions of 30°, 60° and 90° from σ_H is significantly different from that amount for lateral wellbores drilled in the direction of σ_H. The optimum trajectory of the lateral wellbore is reached in case it is drilled with an angle of 15° from the horizon and in the direction of σ_H (Fig. 8).
- In general, the trend of diagram in the NF–SS stress regime is similar to the previous condition. However, under this circumstance the lowest mud pressure is needed for a horizontal lateral wellbore which is drilled in the direction of σ_h (Fig. 9).
- In RF stress regime, the deviation of lateral wellbore direction from horizontal principal stresses and increase of inclination from horizontal situation leads to a more unstable junction. The lateral wellbore in the direction of σ_H and inclination angle of 15° has got the lowest junction mud pressure, and hence its trajectory is the optimum one (Fig. 10).
- The SS–RF stress regime results are analogous with RF condition. Thus, the optimum trajectory of the lateral wellbore is the same as above (Fig. 11).

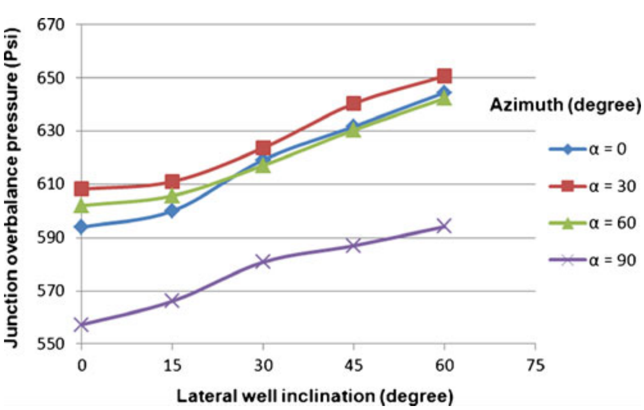

Fig. 9 Minimum overbalance pressure as a function of borehole trajectory in NF–SS stress regime

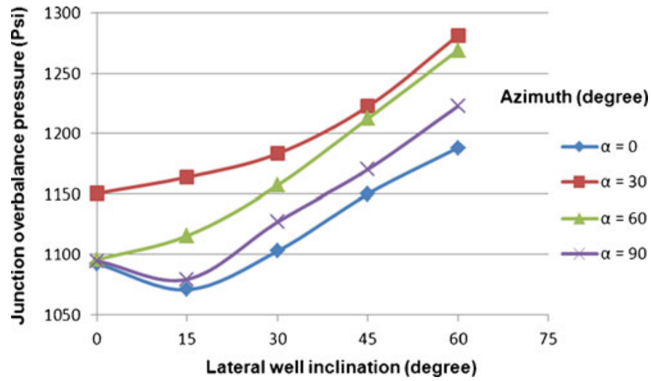

Fig. 10 Minimum overbalance pressure as a function of borehole trajectory in RF stress regime

Comparison of stability in main wellbore, junction and lateral branch

In each stress regime, the plastic zone area in the junction is more than other parts of the multi-lateral well. Consequently, the junction requires more mud pressure compared to the main (vertical) and lateral wellbores. As a result, this section is the most critical part of multi-lateral wells and needs more mud pressure (Figs. 12, 13, 14, 15, 16 and 17).

In hydrostatic stress regime, the stability of the main (vertical) wellbore and the lateral branches is not significantly varied. For instance, the displacement and plastic zone formation around the multi-lateral well, neglecting the mud pressure, for branch with the inclination of 30° and the direction parallel to σ_H are shown in Figs. 12 and

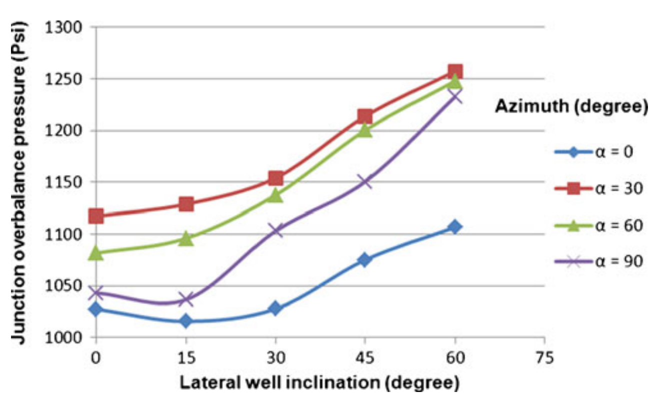

Fig. 11 Minimum overbalance pressure as a function of borehole trajectory in SS–RF stress regime

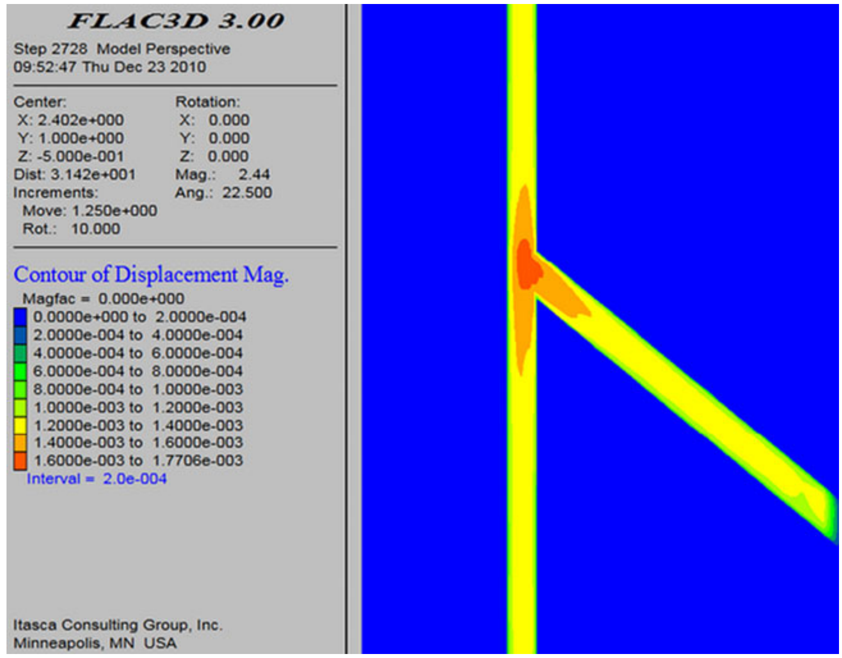

Fig. 12 The displacement contour of a multi-lateral well in hydrostatic stress regime and under no mud pressure for a branch with the inclination of 30° and along the direction of σ_H

13, respectively. In these figures, the displacement and extent of plastic zone are similar in both the main and lateral wellbores, and therefore the mud pressure required in both locations is almost equal as well.

In NF stress regime with isotropic horizontal stresses, the main (vertical) wellbore is more stable than the branch in all trajectories.

In NF stress regime, the main wellbore is more stable than the branches drilled in directions other than σ_h. However, this situation is vice versa when the branches are drilled in the direction of σ_h. In Figs. 14 and 15, for example, the displacement and formation of plastic zone are shown for a lateral wellbore with inclination of 15° and direction of σ_H under no mud pressure condition. In these figures, the main wellbore is more stable than the branch.

In SS stress regime, the branch is more stable than the main (vertical) wellbore in all varied circumstances. In Figs. 16 and 17 this condition is illustrated for a lateral wellbore with the direction parallel to σ_H and inclination of 30°.

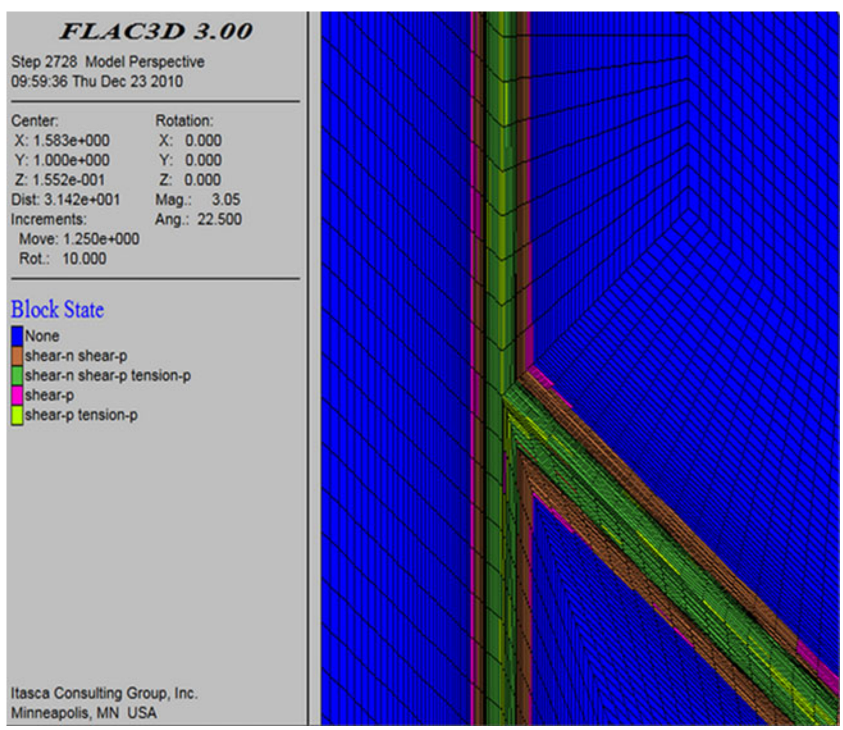

Fig. 13 The plastic zone region (in σ_1–σ_2 plane) of a multi-lateral well in hydrostatic stress regime and under no mud pressure for a branch with the inclination of 30° and along the direction of σ_H

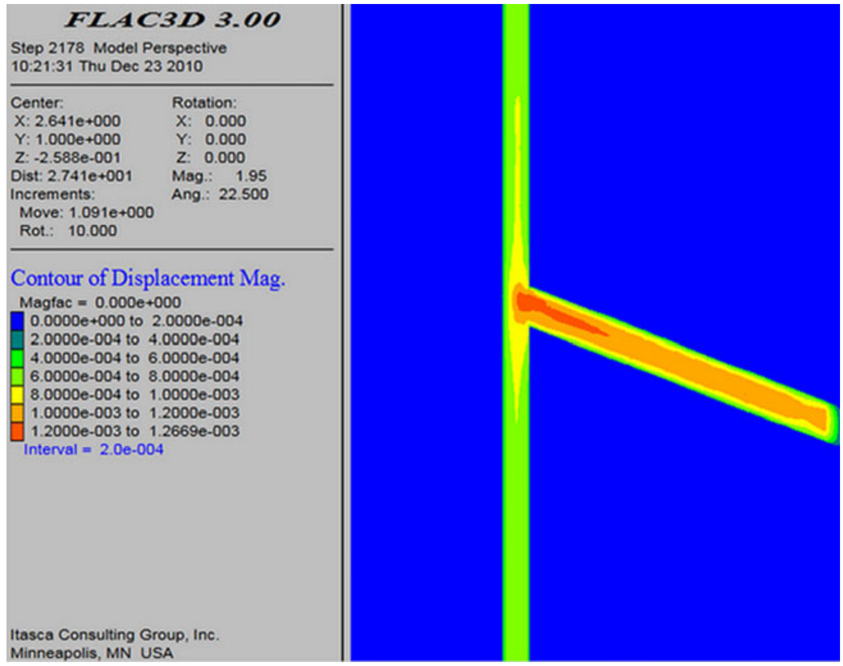

Fig. 14 The displacement contour of a multi-lateral well in NF stress regime and under no mud pressure for a branch with the inclination of 15° and along the direction of σ_H

In NF–SS stress regime, the branches drilled in directions other than 60° and 90° from σ_H direction are more stable than the main wellbore. In the other conditions, directions of 0° and 30° from σ_H, the stability of both main and lateral wellbores is almost the same.

In RF stress regime, the main wellbore is more stable than the branches bored in the direction of σ_h. This situation is the opposite for other directions of lateral wellbores.

In SS–RF stress regime, under all circumstances the branches are more stable than the main wellbore.

Conclusion

In each stress regimes, the minimum required mud pressure for stability of wellbore is more in the junction rather than the main or lateral wellbores. In other words, the junction region is the most crucial part of multi-lateral wells. However, depending on the stress regime, the main wellbore could be more stable than the branches or vice versa.

In isotropic horizontal stress condition, the variation of the lateral wellbore direction has an insignificant effect on the optimum mud pressure.

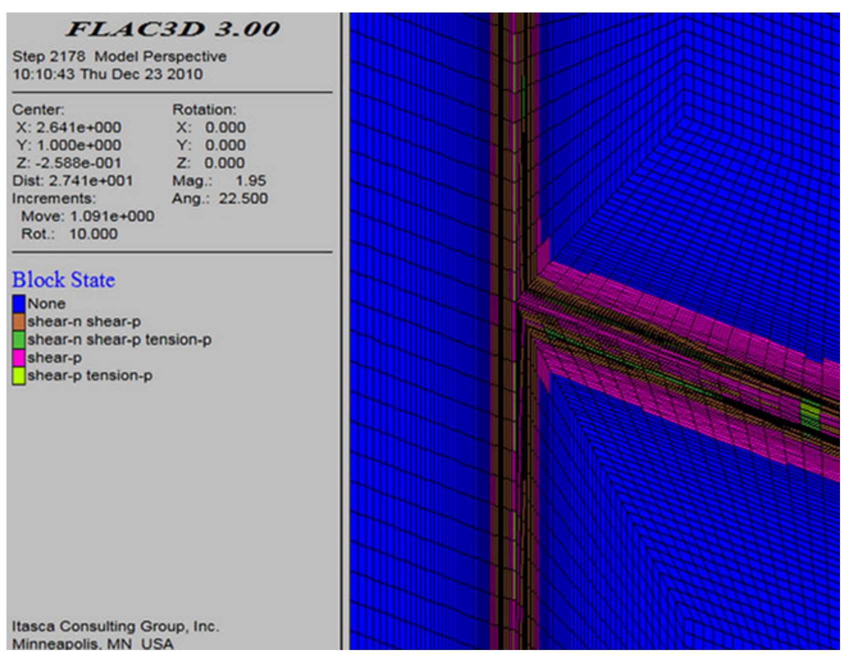

Fig. 15 The plastic zone region (in σ_1–σ_2 plane) of a multi-lateral well in NF stress regime and under no mud pressure for a branch with the inclination of 15° and along the direction of σ_H

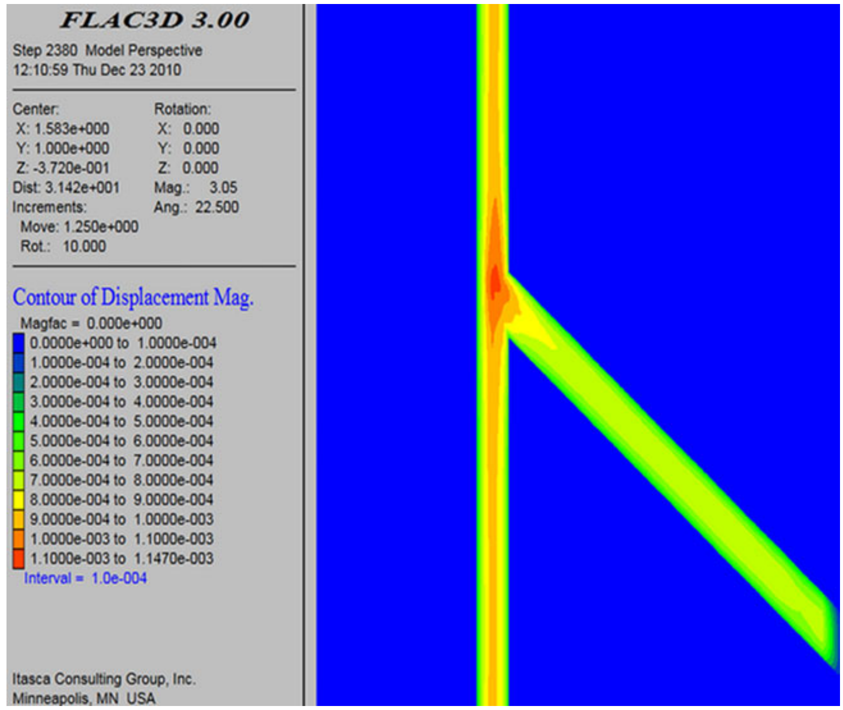

Fig. 16 The displacement contour of a multi-lateral well in SS stress regime and under no mud pressure for a branch with the inclination of 30° and along the direction of σ_H

In NF stress regime with isotropic horizontal stresses, in all varied directions of the branch and also in NF stress regime (with anisotropic horizontal stresses) for branches drilled in the direction of 0°, 30° and 60° from σ_H, by increasing of the lateral wellbore inclination, the instability of the junction reduces. In other stress regimes, in general, the increase of inclination would lead to more instability.

The optimum trajectory of the lateral wellbore, under hydrostatic and NF–SS stress regimes, is horizontal. In NF stress regime with isotropic horizontal stresses, the branch with the steepest inclination (60° in this case) has the optimum orientation. For SS, RF and SS–RF stress regimes, 15° is the optimum lateral wellbore inclination. In NF stress regime (with anisotropic horizontal stresses), the optimum inclination of the branch is contingent on the direction of it.

The optimum direction of the lateral wellbore under SS, RF and SS–RF stress regimes is parallel to σ_H direction. In NF–SS stress regime, this direction is parallel to σ_h.

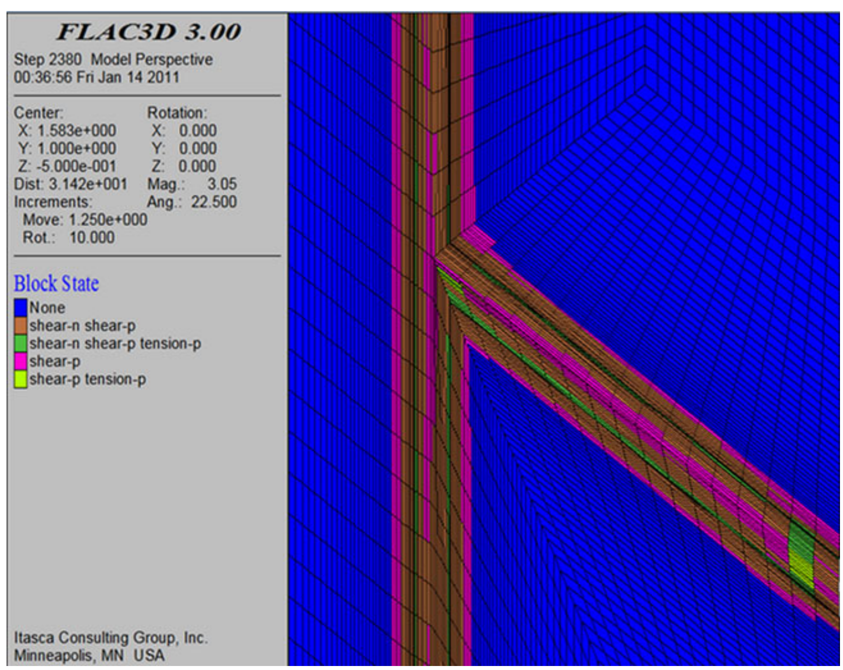

Fig. 17 The plastic zone region (in σ_1–σ_2 plane) of a multi-lateral well in SS stress regime and under no mud pressure for a branch with the inclination of 30° and along the direction of σ_H

Moreover, in hydrostatic and NF (with isotropic horizontal stresses) stress regimes, the optimum direction is in directions other than the direction of the principal horizontal stresses. Under NF stress regime (with anisotropic horizontal stress regime), the optimum direction of the branch is dependent upon its inclination.

The deviation of the lateral wellbore direction from the horizontal stresses increases the stability of the junction in hydrostatic and NF (with isotropic horizontal stresses) stress regimes. This fact is the opposite for RF and SS–RF stress regimes.

Generally, in all in situ stress regimes, the increase of σ_H/σ_h causes the optimum branch trajectory to approach the σ_H direction. In addition, the optimum orientation of the lateral wellbore is parallel to or near the maximum horizontal stress direction.

References

Al-Ajmi A (2006) Wellbore stability analysis based on a new true-triaxial failure criterion. PhD. dissertation, Sultan Qaboos University, Muscat

FLAC3D (2006) Student license. Itasca Consul Group, Inc., USA

Garrouch AA, Lababidi HMS, Ebrahim AS (2004) An integrated approach for the planning and completion of horizontal and multilateral wells. J Pet Sci Eng 44:283–301

Jordan M, Paez R, Umudoro K (2002) New aspects of multilateral well construction. Oilfield Rev 14(3):52–69

McLellan PJ, Hawkes CD (2002) Coupled modeling of borehole instability and multiphase flow for underbalanced drilling. Adv Geotechnol Inc. IADC/SPE

Soliman MY, Boonen P (2000) Rock mechanics and stimulation aspects of horizontal wells. J Pet Sci Eng 25:187–204

Zhang J, Bai M, Roegiers JC (2006) On drilling directions for optimizing horizontal well stability using a dual-porosity poroelastic approach. J Pet Sci Eng 53:61–76