Research on stress distribution regularity of cement sheaths of radial well based on ABAQUS

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Abstract: To ensure desirable outcome of hydraulic fracturing based on ultra-short radius radial systems, it is required to investigate the stress distribution regularity and stability of the cement sheath. On the basis of the theoretical model of the cement sheath stress distribution, a reservoir mechanical model was built using the finite element software, ABAQUS, according to the physical property of a certain oil reservoir of the Shengli oilfield. The stress distribution of the casing-cement-sheath-formation system under the practical condition was simulated, based on which analyses were conducted from multiple points of view. Results show that the stress on the internal interface of the cement sheath exceeds that on the external interface, and fluctuates with higher amplitudes, which means that the internal interface is the most failure-prone. The unevenness of the cement sheath stress distribution grows with the increasing horizontal principal stress ratio, and so does the variation magnitude. This indicates that higher horizontal principal stress ratios are unfavourable for the structural stability of the cement sheath. Both the wellbore quantity of the URRS and the physical property of the material can affect the cement sheath distribution. It is suggested to optimize the quantity of the radial wellbore and use cement with a lower elastic modulus and higher Poisson’s ratio. At last, the impact level of the above factor was analysed, with the help of the grey correlation analysis.

1. Introduction

The ultra-short radius radial system (URRS) refers to a horizontal well with a low radius of curvature, which has recently been applied to the development of low-permeability oil reservoirs, accompanied with hydraulic fracturing\textsuperscript{[1]}.

However, owing to differences of properties, such as the Young’s modulus and Poisson’s ratio, among the cement sheath, casing and formations, the cement sheath first fails once the isolation and fixation system deforms, which indicates that the cement sheath is a weak part of the whole system and the cement sheath failure is one of the major failure modes of the system\textsuperscript{[2]}.

For desirable reservoir stimulation based on the URRS and hydraulic fracturing, it is required to study the stress distribution regularity in the cement sheath and the cement sheath stability. Previous studies often built theoretical models of the cement sheath alone, and thus are incapable of effectively and truly reflecting the stress distribution of the cement sheath as part of the casing-cement-sheath-formation coupling system. Especially, reports on the stress distribution regularity of perforated or windowed cement sheaths are hardly seen. Nevertheless, the finite element method-based software, ABAQUS, can establish mechanical models that are consistent to the reality, through which stress states
of the cement sheath and the drilled hole can be directly observed and corresponding specific stress values can be read\[^3\]. Analyses based on such acquired data are more reliable and more realistic\[^4\].

Given the aforementioned, a three-dimensional elastoplastic cased wellbore model was built using ABAQUS, on the basis of the lithological and physical properties of a certain reservoir of the Shengli oilfield. The model was used to study the effects of the horizontal principal stress ratio (HPSR), elastic modulus and Poisson’s ratio of the cement sheath, etc. On the stress distribution in the cement sheath. The simulation results, which truly and directly reflect the reality, provide meaningful reference and guidance.

2. Numerical simulation of cement sheath stress distribution

The practical lithological and physical property information of a specific oil reservoir of the Shengli oilfield was used for the establishment of the mechanical model in ABAQUS. The detailed model parameter is seen in Table 1.

| Table 1. Model parameters of the simulation |
|------------------------------------------|
| Casing Diameter, mm | ID 180 | Casing Elastic Modulus, GPa | 230 |
| OD 190 | Cement Sheath Elastic Modulus, GPa | 30 |
| Cement Sheath Diameter, mm | ID 190 | Formation Elastic Modulus, GPa | 12 |
| OD 240 | Porosity, % | 33 |
| Wellbore Diameter, mm | 240 | Pore Pressure, MPa | 15 |
| Formation Diameter, m | 100 | Overburden Pressure, MPa | 35 |
| Formation Thickness, m | 0.5 | Maximum Horizontal Principle Stress, MPa | 30.98 32.16 33.19 |
| Wellbore Diameter of URRS, mm | 50 | Minimum Horizontal Principle Stress, MPa | 28.16 26.80 25.53 |
| Length of URRS, m | 50 | Horizontal Principal Stress Ratio | 1.1 1.2 1.3 |

The horizontal principal stresses were adjusted simultaneously in the way that the resultant force of the two horizontal principal stresses was constant\[^5\].

The unit of force in the simulation was N and that of stresses was MPa. Moreover, it was defined that the tensile stress should be positive. The Z axis was the direction of the vertical stress, and the X axis is the one of the maximum horizontal principal stress. The azimuth was noted as the counterclockwise rotating angle from the positive direction of the X axis.

The “Max Principle” in the simulation result is the stress with the highest value\[^6\], which, in a model that defines the tensile stress as positive, stands for the “maximum tensile stress” or “minimum compressive stress”. The Mises stress in the simulation follows the distortion energy theory.

2.1 Stress distribution regularity of the casing-cement-sheath-formation system

With a horizontal principal stress ratio (HPSR) unequal to 1, results of simulation present similar regularity. Therefore, only the simulation results of cases respectively with HPSRs of 1 and 1.3 are presented here. The simulation results and the zoomed-in images are shown below:
Figure 1. Stress distribution maps respectively with HPSRs of 1 and 1.3

It is seen from Fig. 1 that with a HPSR of 1, the Mises stress and the Max Principle stress are found being uniformly distributed in the casing, cement sheath and formation. In the case of unequal horizontal principal stresses, the stress distributions in the three part are all non-uniform, and the phase difference of 90° exists between the maximum and minimum stresses. The maximum Mises stresses all occur along the direction of the minimum horizontal principal stress, which indicates plastic failure is most likely to happen along this direction. The maximum Max Principle stress are all found in the maximum horizontal principal stress direction, and accordingly in this direction the tensile limit is most likely to be reached and then tensile failure initiates. In the meantime, the direction of the maximum horizontal principal stress is also the one with the minimum fracture pressure in terms of hydraulic fracturing.

With a HPSR of 1, it is illustrated that the stress gradient is ring-shaped, centered at the wellbore and transferred to the far-away-from-wellbore region. With horizontal principal stress differences, the stress gradient presents similar distribution regularity, except that the ring shape changes into irregular compressed shapes. Similar observation is also found in the cement sheath and casing.

2.2 Stress distribution regularity of the internal and external interfaces of cement sheaths

On the basis of the cement sheath stress obtained from the above model, the stress distribution regularity on the internal and external interface of the cement sheath was studied.

The Mises stress on the internal interface is below that on the external interface, while the Max Principle stresses on the internal and external interfaces are approximately consistent. It is safe to say that with a HPSR = 1, the stress distribution in the cement sheath is uniform and the stress state is stable.

The stress distributions along the thickness of the cement sheath with varied HPSRs are similar to each other. Thus only the case of a HPSR = 1.3 is presented in Fig. 2 for discussion.
Fig. 2 shows that with uneven horizontal principal stresses, the Mises and Max Principle stresses both exhibit cyclic variation with respect to the azimuth, and the cycles are both 180°. The phase difference between the maximum Mises and Max Principle stresses is 90°. The stress variation decreases in magnitudes as the position approaches the external interface of the cement sheath, which suggests the stress distribution is more stable. The maximum and minimum Mises and Max Principle stresses are all found on the internal interface of the cement sheath. Therefore, the stress state of the internal interface of the cement sheath is the most complicated, and this position is the most failure-prone.

2.3 Factors affecting stress distribution in cement sheaths
The stress distribution of the cement sheath is affected by the horizontal principal stress difference, the material characteristics of the cement sheath, etc. The variation regularity can be concluded as follows:
From Fig. 3, it is seen that with the case of a HPSR = 1 used as the datum, the Mises stress declines (lower than the datum value) with the rising HPSR in cases of lower azimuths, while the Max Principle stress grows (higher than the datum value), which indicates high possibility of tensile failure. In cases of higher azimuths, the Mises stress grows (higher than the datum value) with the climbing-up HPSR and yet the Max Principle stress falls (lower than the datum value), which can be explained as tendency to plastic (shear) failure.

The maximum and minimum Mises stresses increase nonlinearly with the growth of the cement sheath elastic modulus, while linear decease is found in terms of the Max Principle stress. This indicates that higher cement sheath elastic moduli can offset the risk of tensile failure of the cement sheath, and yet greatly stimulate the possibility of plastic failure. Given the Max Principle stress is always negative, the Mises stress is the priority in case of plastic failure. The inflection point occurs with the cement sheath elastic modulus of about 30 GPa, beyond which the difference between the maximum and minimum stresses gradually grows, the heterogeneity of cement sheath stress distribution intensifies, and the structural stability of the cement sheath is compromised.

The maximum and minimum Mises and Max Principle stresses approximately linearly decrease with the growing Poisson’s ratio of the cement sheath, as is shown in Fig. 7. Thus it is clear that by raising up the Poisson’s ratio of the cement sheath, the risk of the cement sheath failure can be effectively reduced and the cement sheath structure stability be improved.

After drilling through the cement sheath, the Mises stress considerable grows and generally surpasses that before perforation. However, although certain growth is also found in the Max Principle stress, the minimum Max Principle stress at the local area of the drilled hole is below that before perforation. Apparently, the stress concentrates at the radial wellbore and the stress distribution regularity before windowing has been altered. The phase difference at the entrance hole of the URRS between the Mises and Max Principle stresses remains as 90°, and it is illustrated in Fig. 8 that between the locations of the peak Max Principle and Mises stresses exists a azimuth difference of 15°.

At the entrance of the URRS, the peak Mises stress can reach about 80 MPa, increasing by 160.21% from that before windowing. Meanwhile, the peak Max Principle stress increases by 180.48%. The growth of the two stresses declines slightly with the increase in the number of holes. Radial drilling significantly changes the stress distribution in the cement sheath, which leads to higher risks of both plastic and tensile failure of cement sheaths.
3. Conclusions
(1) An ABAQUS-based finite element model was built, based which the stress distribution regularity in the cement sheath was directly observed and effectively studied. A phase difference of 90° exists between the maximum Mises and Max Principle stresses in the cement sheath. Before radial drilling, tensile failure is likely to occur in the direction of the maximum horizontal principal stress, while in the direction of the minimum horizontal principal stress plastic failure tends to happen.

(2) Along the thickness of the cement sheath, the stress changes. Compared that on the external interface, the stress variation on the internal interface of the cement sheath is higher in magnitudes. In general, the peak values of stress are all found on the internal interface, which indicates the internal interface is a vulnerable interface and most failure-prone.

(3) The stress distribution and its variation of the cement sheath are affected by multiple factors. Numerical simulation demonstrates that the cement sheath stress fluctuates with higher amplitudes and the stability of the cement sheath declines, as the horizontal principal stress ratio grows. It is suggested that cement materials with a low elastic modulus and high Poisson’s ratio should be used in the well construction to improve the cement job quality.

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