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Research article

Problems in the wellbore integrity of a shale gas horizontal well and corresponding countermeasures

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Abstract

In the Changning—Weiyuan national shale gas demonstration area, SW Sichuan Basin, the wellbore integrity damage occurs in some shale gas wells and has direct effect on the gas production rate of single shale gas horizontal well. After statistics analysis was performed on the problems related with wellbore integrity, such as casing damage, casing running difficulty and cement sheath blow-by, the multi-factor coupling casing stress calculation and evaluation mode laws established. Then study was conducted on the influential mechanism of multi-factor coupling (temperature effect, casing bending and axial pressure) on casing damage. The shale slip mechanism and its relationship with casing sheared formation were analyzed by using the Mohr—Coulomb criterion. Inversion analysis was performed on the main controlling factors of casing friction by using the developed casing hook load prediction and friction analysis software. And finally, based on the characteristics of shale gas horizontal wells, wellbore integrity control measures were proposed in terms of design and construction process, so as to improve the drilling quality (DQ). More specifically, shale gas well casing design calculation method and check standard were modified, well structure and full bore hole trajectory design were optimized, drilling quality was improved, cement properties were optimized and cement sealing integrity during fracturing process was checked. These research findings are significant in the design and management of future shale gas borehole integrity.

Keywords: Shale gas; Wellbore integrity; Casing damage; Shale slip; Drilling quality (DQ); Sichuan Basin; Changning—Weiyuan; National shale gas demonstration area

As a core index [1] in drilling and completion of horizontal wells in the development of shale gas, wellbore integrity may play an important role in ensuring the safety of shale gas wells during the entire service period. In addition, wellbore integrity is a key attribute to protecting the hole from structural damages and maintaining desirable performances. Wellbore integrity may also ensure downhole safety and promote productivity of individual wells in shale gas development. In recent years, studies have been performed on wellbore integrity from different perspectives. As far as engineering is concerned, wellbore integrity include two key components: drilling quality (DQ) and completion quality (CQ) [2,3].

The Changning—Weiyuan national shale gas demonstration area in southwestern Sichuan Basin suffered some problems related to wellbore integrity of some shale gas wells since its exploration and development in 2013. Such problems include difficulties in tripping in casings in horizontal well intervals, cement sheath blow-by and severe casing damage. It is especially worth mentioning that casing damages may lead to difficulties in the installation of bridge plugs and the milling of such bridge plugs by coiled tubing. In extreme cases, fracturing operations were forced to be abandoned in certain intervals. All such problems may negatively affect enhancements in productivity in individual shale gas horizontal wells.

With regard to wellbore integrity in horizontal shale gas wells, Adams and Sugden et al. [4,5] analyzed major factors that may affect the generation of abnormal loads on production

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casings in shale gas wells of the United States. They proposed, for the first time, the concept of irreducible fluid contraction in annular spaces during fracturing. In addition, they reviewed hazards in casing design of shale gas wells. With consideration to the present situations and the specific features of wellbore integrity in horizontal shale gas wells, CNPC Drilling Research Institute conducted researches on correlation between pressures and temperatures of irreducible fluids in annular spaces, impacts of shale slip on casing damage and major controlling factors for difficulties during casing installation. During the course, models for assessments and calculation of casing damages induced by multiple causes have been constructed to reveal mechanisms and patterns of casing damages, shale slip, difficulties in casing installation and other aspects. Relevant researches may provide valuable guidelines for design and management of wellbore integrity during shale gas development.

1. Wellbore integrity problems in horizontal shale gas wells

1.1. Frequent occurrence of casing damage

Statistics show that 13 wells out of 33 wells with large-scale hydraulic fracturing operations before 2015 in the Changning−Weiyuan area suffered casing damages or deformations of various degrees. In the Changning Block, 9 wells out of the 14 horizontal wells with fracturing operations experienced abnormal conditions. It can be seen that wellbore integrity is a prominent problem (See Fig. 1). Analysis results show that these casing damages may have three specific features. First, majority of casing damages are concentrated around Point A (Landing point) in the horizontal well. To be more specific, 62.5% casing damages are distributed around the point, whereas the remaining 37.5% may be distributed in other areas. Second, all casing damages occur during hydraulic fracturing. Third, certain casing damage points are distributed around the contacts of different formations, or around the faults identified through logging data interpretation. With significant changes in lithologic features, these formations have high heterogeneity in both geomechanics and crustal stress.

1.2. Difficulties in casing installation

Difficulties in casing installation can be frequently encountered during production casing installation in shale gas wells in the Changning−Weiyuan area. For example, in Well HJBH6-8, the hook disengaged from the production casing at the well depth of approximately 3500 m. Difficulties in the lowering of the production casing were encountered at approximately 3757 m. So it is necessary to move the casing up and down with amplitudes of 2−3 m to install the production casing properly. From the depth of 3772 m, amplitudes of such movements were increased to 5−6 m. Further down to the depths of 4185−4208 m, more severe difficulties were encountered. So it is necessary to enhance wellhead pressures, or even “bump in” (Fig. 2) to install the production casing. Upon installation of the ⌀127 mm production casing in Well CNH2-1 (at well depth of 4177.95 m), joints on female screw of the casing were found to be deformed. Great difficulties were also encountered during the installation of the ⌀127 mm production casing in Well CNH2-3 at the depth of 3060 m. The casing was moved up and down repeatedly for about 1 h before proper installation.

1.3. Difficulties in maintaining cement sheath integrity

In the shale gas demonstration area, cement sheath integrity is subject to impacts of high-density oil-based drilling fluids which are difficult to be flushed or displaced, difficulties in centralization of casing, high formation pressure coefficients in shale, high pressures and low temperatures during fracturing. Consequently, severe problems may be encountered, especially in long horizontal intervals.

2. Analysis on the wellbore integrity of horizontal shale gas wells

2.1. Mechanisms of casing damage based on multi-factor coupling

In view of temperature effects, pressure effects, bending effects and other factors may affect performances of casing, assessment and calculation models for casing damages

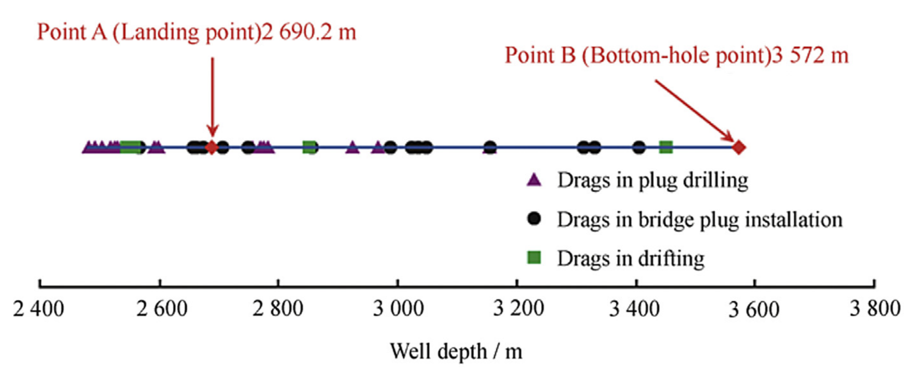

Fig. 1. Statistics on points with casing damages at different well depths in the Changning−Weiyuan Area.

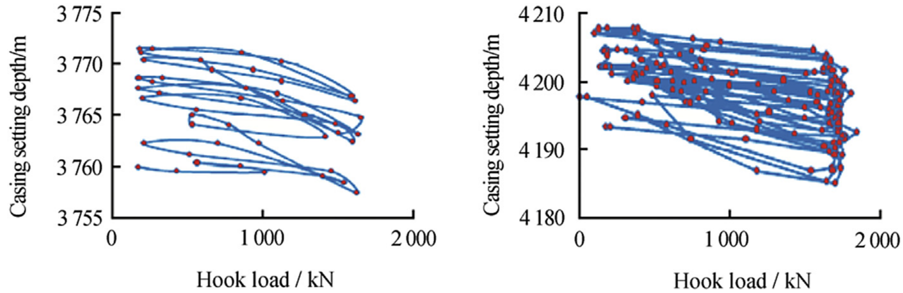

Fig. 2. Changes in hook load when difficulties in casing installation were encountered at different setting depths in Well HJBH6-8.

induced by multi-factor coupling were constructed to analyze major factors that may affect casing damages.

2.1.1. Calculation of temperature field during the injection of large-volume fracturing fluids in the borehole

During the implementation of large-scale volume fracturing in shale gas development, temperatures within the borehole may drop fast with high-speed injection of fracturing fluids. By using the finite difference model for heat exchange between fracturing fluids and surrounding formations, distribution of temperature fields within the borehole during operations in summer and winter can be calculated, respectively.

For example, in Well CNH3-1, the temperature in shale reservoir is 100 °C, and the ground temperature of the injected fracturing fluids in winter is 3 °C, whereas that in summer is 20 °C with average fracturing fluid injection speed of 8 m^3/min, the maximum pump pressure on surface is 78 MPa and the continuous injection duration is 3.67 h. Through calculation by using the model, it can be seen (Fig. 3) that, during operations in winter, bottom-hole temperatures may drop down to 82.08 °C with temperatures of production casing at 17.92–24.08 °C in horizontal intervals with depths of 2800–4010 m. During operations in summer, bottom-hole temperatures may drop down to 65.56 °C with temperatures in production casing at 34.44–40.24 °C.

2.1.2. Predictions of contraction and pressures of irreducible fluids in annular spaces

In intervals with poor-quality cementation, certain parts of cement sheath may have vacant spaces containing high-pressure fluids. During high-speed fracturing operations, cooling effects of fracturing fluids on casing may lead to shrinkage of high-pressure fluids contained in such vacant spaces of cement sheath (Fig. 4). Under such circumstances, pressures within them may drop rapidly. Since shale formations are tight with extremely low permeability of 10^{-4} mD, high-pressure fluids contained may not be supplemented by surrounding formation water in timely manner. Eventually, external pressures on casing pipes may drop significantly.

The equations of water phase behavior based on international standards can be deployed to determine the dynamic changes of fluid pressures in annular vacant spaces. If the initial pressure of fluids in annular space is 60 MPa and the temperature is 100 °C, high-speed injection of fracturing fluids may reduce temperatures of irreducible fluids within the annular space. Due to incompressibility of water, pressures in annular vacant spaces may also drop rapidly. In extreme cases, fluid pressures in such vacant spaces may approach 0 MPa when the temperature of irreducible fluids in annular spaces reduces to 58 °C, as shown in Fig. 5.

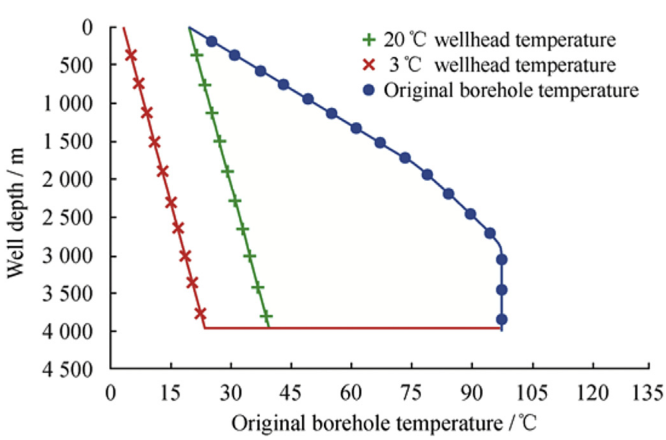

Fig. 3. Distribution of temperatures in production casing at horizontal intervals of Well CNH3-1.

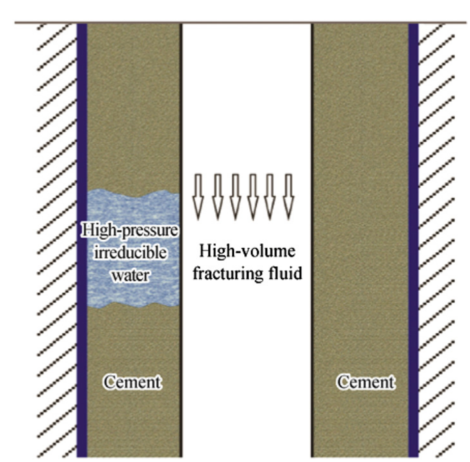

Fig. 4. Annular vacant spaces of a cemented horizontal shale gas well.

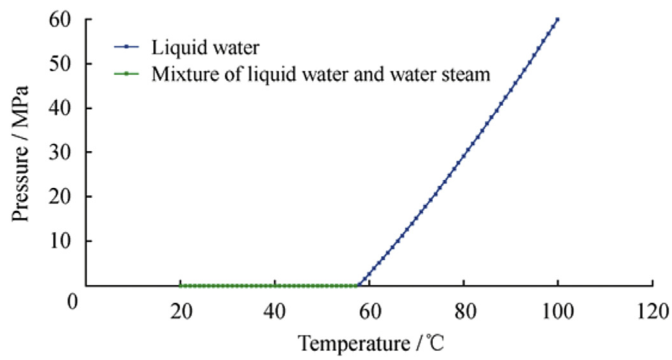

Fig. 5. Dynamic changes of pressures of fluids contained in vacant spaces of cement sheath in a horizontal shale gas well.

2.1.3. Impacts of shrinkage of irreducible fluids in annular spaces on internal pressure strength of casing

Shrinkage of fluids in annular spaces may lead to dramatic drops in external pressures on casing. Consequently, effective internal pressures on casing may increase. Again, Well CNH3-1 may be taken as an example to assess the impacts of shrinkage of annular fluids on internal pressure strength of production casing. All the following calculations are based on actual conditions of the well.

① Internal pressure strength of casing is 102.5 MPa without regard to the impacts of axial stress on internal pressure strength. ② Cement sheath is missing at the depths of 2980–2983 m. Initial pressure of fluids in annular space is 60 MPa (the predicted actual formation pressure) and temperature is 100 °C. ③ Maximum pumping pressure on surface during fracturing is 78 MPa. Calculation results show that, with shrinkage effects of irreducible fluids contained in annular spaces considered, safety coefficient of casing pipe against internal pressures is 0.958. It can be seen in Fig. 6 that the safety coefficient against internal pressures in Well CNH3-1 is below 1, damages related to internal pressures may occur.

2.1.4. Impacts of hole curvatures on casing strength in horizontal wells

Generally speaking, borehole curvature may generate tension and pressure on both sides of casing. Accordingly, both collapse strength and internal pressure strength of such casing may be reduced. The P110 casing pipe (⌀139.7 mm) can be deployed to determine the impacts of borehole curvature dogleg severity on casing strength. The casing concerned has wall thickness of 11.75 mm, modulus of elasticity of 206×10^6 kPa and yield strength of 758 MPa. Calculation results show that, with the hole curvature of 10°/30 m, internal pressure strength of casing under pressure may approximately drop by 6%, as is shown in Fig. 7. On the tension side, collapse strength of casing may drop by 4.64% at the hole curvature of 5°/30 m, or drop by 9.85% at the hole curvature of 12°/30 m. Moreover, impacts of borehole dogleg severity on collapse strength are also significant, as shown in Fig. 8.

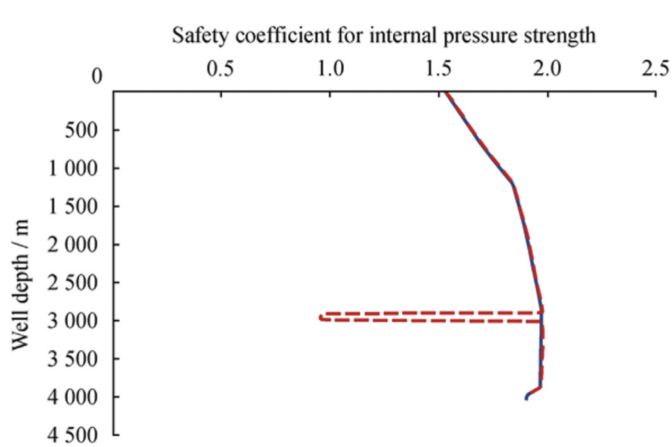

Fig. 6. Internal pressure strength of casing in Well CNH3-1.

2.1.5. Impacts of temperature drop in the wellbore on collapse strength of casing

According to the above analyses, temperatures in borehole of horizontal interval may drop dramatically during high-speed fracturing. Such dramatic drops of temperatures may lead to casing shrinkage and corresponding increases in tensile stress. Impacts of changes in temperatures on collapse strength of casing can be determined in accordance with the tensile stress induced by temperature effects and calculation equation

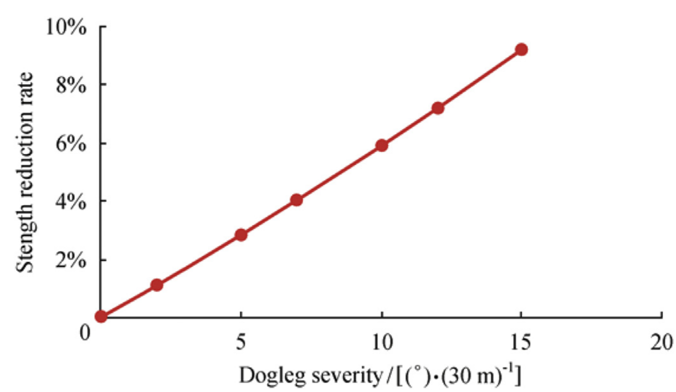

Fig. 7. Internal pressure strength reduction rate of casing vs. dogleg severity of borehole.

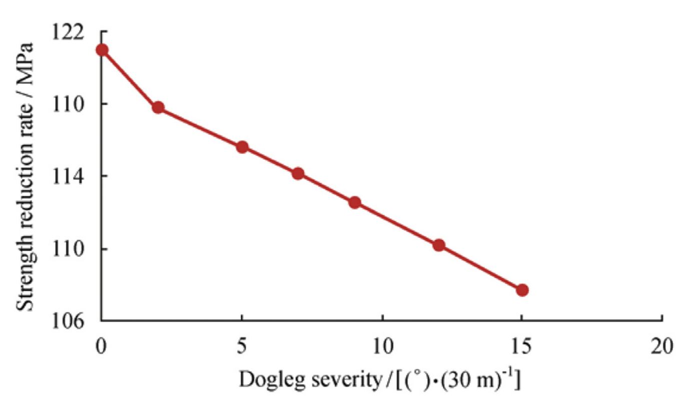

Fig. 8. Collapse strength reduction rate of casing vs. dogleg severity of borehole.

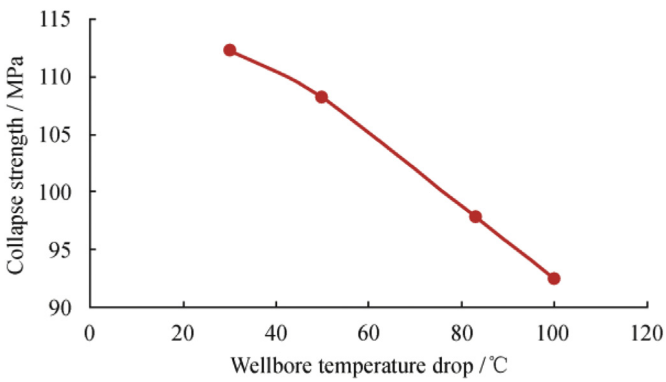

Fig. 9. Impacts of wellbore temperature drop on casing's collapse strength.

[6] for the tri-axial collapse strength. For example, Well CNH3-1 has casing with diameter of ⌀139.7 mm, steel grade of P110 and wall thickness of 11.1 mm. When temperatures around Point A dropped to 83 °C, collapse strength of the casing may reduce by19.16%, from 121 MPa to 97.82 MPa, as shown in Fig. 9.

2.1.6. Verification of casing strength under multi-factor coupling in horizontal shale gas wells

Production casing in horizontal shale gas wells may subject to the following four additional loads: ① removal of regional external forces induced by shrinkage of fluids in vacant spaces of cement sheath; ② impacts of borehole curvature on internal pressure strength and collapse strength of casing, ③ temperature effects induced by borehole temperature reductions; and ④ super-high pressures formed outside the casing during multi-stage fracturing. These are major risks for casing damages in horizontal shale gas wells.

In extreme working conditions, coupling of the abovementioned factors should be considered to verify internal pressure strength and collapse strength of casing in Well CNH3-1 in the Changning–Weiyuan area. It can be seen in Fig. 10 that, with shrinkage effects and bending stress of fluids in annular spaces at the depth of 2980 m, together with other coupling loads, overall stress on the casing will exceed the minimum yield strength (Y_p) enveloping line of casing. Consequently, it can be seen that internal pressure strength of casing at this position can no longer satisfy the requirements of fracturing operations.

In accordance with calculation results, weight map of multi-factor coupling that may affect internal pressure strength of casing can be drawn, as shown in Fig. 11. It can be seen that reductions in internal pressure strengths induced by temperatures are significant.

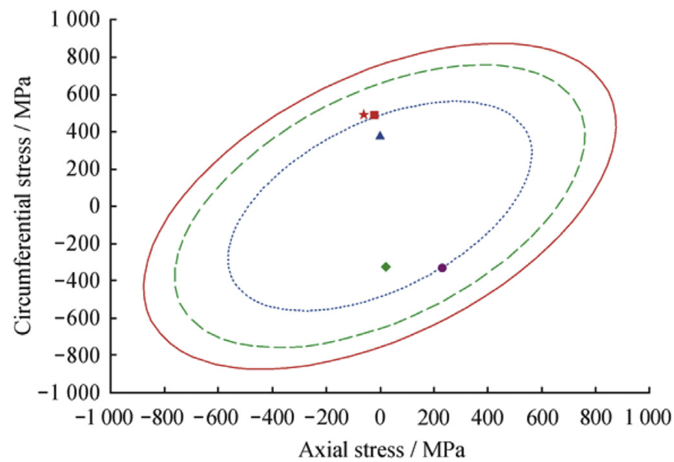

Fig. 10. Comprehensive assessments on casing damage under multi-factor coupling in Well CNH3-1. Note: Red line represents the minimum yield strength Y_p enveloping line of casing with steel grade of P110; black line represents $0.875Y_p$ enveloping line, which can be used to calculate internal pressure strength of the API casing; dash line represents equivalent Y_p of the minimum internal pressure strength of casing threads; green star represents the originally designed internal pressure strength at the depth of 2980 m; red square represents verified internal pressure strength with consideration to annular shrinkage and casing bending; red five-pointed star represents verified internal pressure strength with consideration to annular shrinkage/casing bending/friction resistance of casing; diamond represents verified collapsing strength under bending stress; red circle represents verified collapsing strength with consideration to bending stress and temperature effects of casing.

2.2. Relationship between shale slip and casing damage

During fracturing of shale gas wells, fluids with volumes over 4×10^4 m^3 and sands of thousands of tones may be injected in a horizontal interval with a total length of 1500 m within a very short time. Such fracturing fluids and sands are incompressible. So formations are subject to compression to contain these materials. When compressive stresses reached certain level, formations may experience shear dislocation along shale bedding or interfaces with changes of lithologic properties. Eventually, such dislocations may induce casing deformation.

Shale can be classified as a typical transverse isotropic material with large quantity of bedding planes contained. Shale slip (shear deformation) can be analyzed by using the Mohr–Coulomb criterion:

$$\tau_{\max} = c + \sigma_n \tan\phi$$

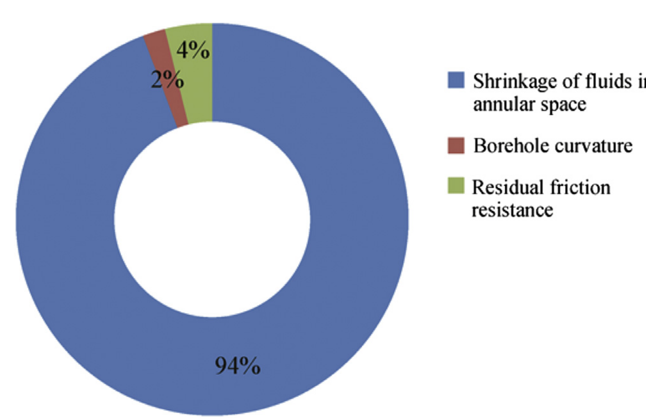

Fig. 11. Distribution of weights in multi-factor coupling for internal pressure strength in Well CNH3-1.

in which, τ_{max} is the maximum allowable shear stress on shale; c is cohesion of shale; σ_n is normal stress among slippage surfaces; ϕ is internal friction angle.

Generally speaking, shale has relative weak bounding strength between bedding planes (i.e. with minor τ_{max}). Accordingly, different layers may experience slippage along such bedding planes under shearing. It is especially true during hydraulic fracturing. Whenever hydraulic pressures exceed the sum of vertical geostress and the bounding strength between bedding planes, such bedding planes may get slightly disengaged. Moreover, fracturing fluids may invade such bedding planes. Later, the normal stress (σ_n) between two neighboring bedding planes may decrease significantly due to supporting effects of fracturing fluids. At the same time, lubrication effects of fracturing fluids may effectively reduce friction coefficients ($\tan\phi$) between different layers. Under such circumstances, relative slippage between different layers may become much easier. When casing is installed in the area with slipping shale and forms high angles with the slip direction (for example vertical to the slippage plane) shear deformation will occur.

At the same time, different mechanical properties of shale and uneven distribution of fracturing fluids in different reservoir formations may lead to shear deformation of rock formations, which can be verified by Micro micro-seismic data acquired during fracturing can verify existence of such conditions. It can be seen in Fig. 12 that quantities of micro-seismic data acquired on at different elevations may vary significantly. These differences may indicate differences in features and volumes of deformation at various depths. When such differences are high enough, shear slippage may occur between different layers [7,8].

Fig. 13 shows the mechanisms related to shear deformation of casing induced by formation slippage. It is worth noticing that casing pipes are made of ductile materials with strengths much higher than those of cement sheath and formation, which can be classified as brittle materials. Consequently, cement sheath and shale may experience intensive mechanical interactions in areas around shear deformation of casing. Usually, these physical interactions may be accompanied by fragmentation of various degrees.

2.3. Major controlling factors for proper installation of production casing

Difficulties in casing installation have been encountered in horizontal intervals of some shale gas wells. In some cases, rotary tools were deployed, or through “lifting and bumping” to install the casing. In extreme cases, it was necessary to trip out casing, drift the well before re-installation. Difficulties in casing installation may lead to multiple bending, stretching and impacting of such casing. Consequently, probability of damages may also increase. In addition, improper installation of casing may negatively affect the wellbore integrity.

Inverse analyses were performed on friction resistance of casing by using independently developed software for predicting hook loads and analyzing friction resistance during casing installation.

Fig. 14 shows the inversion results of friction resistance during the installation of a ⌀139.7 mm casing in Well HJBH6-1. Moreover, the 0–1438 m interval in the borehole has a ⌀222.4 mm casing installed, whereas the 1438–4150 m interval is an open hole of ⌀215.9 mm. Density of drilling fluids used is 2.00 g/cm^3. It can be seen in Fig. 14 that the green inversion plots coincided well with the actual hook loads. The equivalent friction coefficient (EFC) within the intermediate casing can be roughly determined to be 0.30, whereas the EFC within the open hole is 0.40. During field operations, casings in the well were installed without any difficulties.

Fig. 15 shows the inversion of friction resistance during the installation of a ⌀127 mm casing in Well CNH2-3. Moreover, the 0–2152 m interval in the borehole has ⌀173.8 mm casing installed, whereas the 2152–3491 m internal is an open hole of ⌀168.3 mm. Density of drilling fluids used is 2.11 g/cm^3. The EFC within the intermediate casing can be roughly determined to be 0.20. Within the open-hole interval, the EFC gradually increases from 0.40 to 0.45–0.50. During field operations, difficulties in casing installation were encountered with multiple “lifting and bumping”. In addition, casing damages were caused during fracturing in later stages.

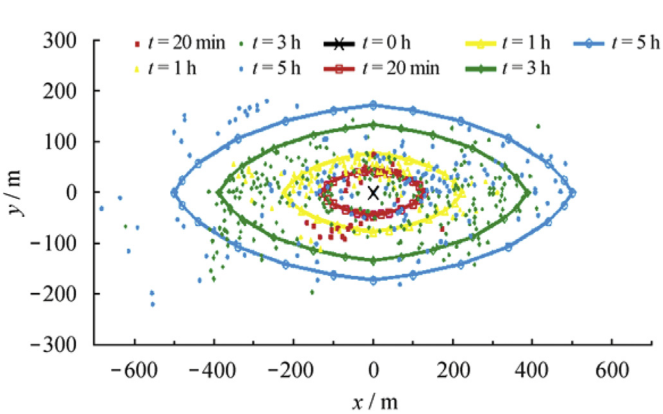

Fig. 12. Distribution of micro-seismic data on the xy plane.

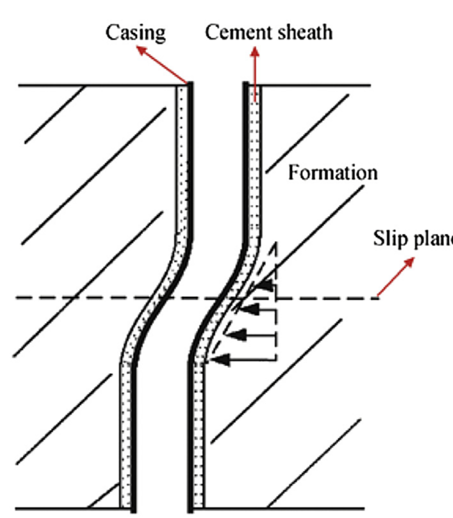

Fig. 13. Shear deformation of casing.

There are significant differences in frication resistances in casings of these two wells predominantly due to the differences in borehole trajectories, such as different kick-off points and azimuth variation, and differences in clearances between open-hole intervals and casings. Without consideration to borehole enlargement, the annular clearance in well HJBH6-1 is 75.9 mm, whereas that in well CNH2-3 is 41.3 mm. Minor annular clearances are probably one of the key reasons for difficulties in casing installation; differences in quantity of casing centralizers deployed and casing rigidity. In addition, there are also differences in borehole conditions, such as conditions of bottom-hole and existence of cutting beds.

3. Measures for maintaining wellbore integrity

3.1. Optimize design to improve the stress conditions of casings

As for production casings in horizontal shale gas wells, shrinkage effects of high-pressure irreducible fluids in annular spaces induced by dramatic drops in temperatures during volume fracturing, together with coupling of other multiple factors are major controlling factors for casing damage. It is necessary to modify calculation methods and calibration standards for casing design to establish new standards for shale gas wells. Cares should be taken during design and construction to improve stress conditions of casing in vicinity of Point A to avoid overlapping of unfavorable conditions. In addition, suitable casing materials should be selected with wall thicknesses enhanced to promote resistance of casing against damages.

Bedding features and hygroscopic expansion of shale [9] may induce formation slippage and eventually induce shear damage of casings. Cares should be taken during design to optimize azimuth and directions of horizontal well trajectory to minimize risks related to shear damage of casings induced by shale slippage.

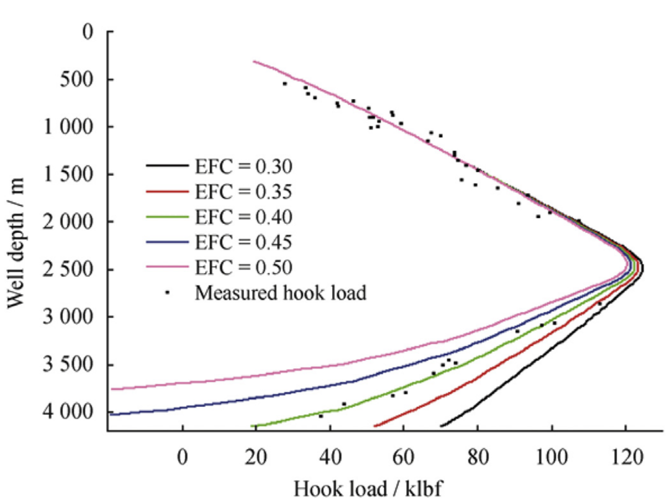

Fig. 14. Inversion of friction resistance in Well HJBH6-1. (Note: 1 klbf = 4.45 kN, the same below).

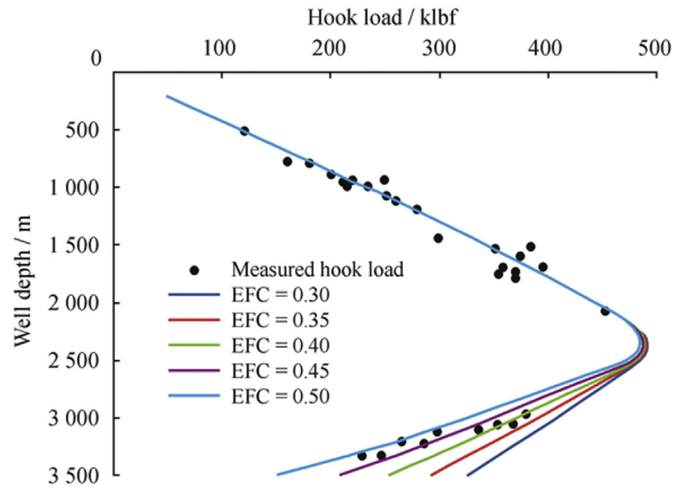

Fig. 15. Inversion of friction resistance in Well CNH2-3.

3.2. Take proper measures to enhance drilling quality

Borehole structures should be further optimized by selecting casing pipes with suitable sizes. Formation, drilling, fracturing, production and other operational conditions should be reviewed comprehensively to determine the most suitable length of horizontal intervals. Through optimization of positions of kick-off points, dogleg severity can be reduced to minimize the bending stress of casings.

3.3. Optimize borehole trajectory design and control technologies to ensure the proper installation of casings

Borehole trajectory design for a well should be optimized to implement strict control over hole curvatures. Suitable drill bits, screws and guiding tools should be deployed for drilling horizontal intervals to ensure desirable capabilities of trajectory control and to obtain smooth boreholes [10]. Cares should be taken to maximize the clearance between boreholes and casings to enhance the compatibility between casings and bending boreholes. Prior to the installation of casings, it is necessary to determine casing rigidity after the installation of centralizers. In addition, the calculated rigidity should be compared with that of drilling and drifting tools. Rigidity of casings should be lower than that of drilling or drifting tools. Cares should also be taken to maintain borehole cleanness to facilitate drifting operations. Floating joints should be deployed if necessary.

3.4. Optimize cementing processes to enhance cement sheath integrity

Since large-scale fracturing operations in shale gas wells may present high demands for the properties of cement, it is necessary to promote structural and sealing integrity of cement sheath in horizontal well intervals for shale gas intervals.

Cares should be taken during design and implementation of cementing operations to optimize the properties of cement and to verify sealing integrity of cement sheath during fracturing. Materials with extra toughness should be deployed to achieve cement sheath with high strength and low modulus of elasticity [11,12] to maintain the structural integrity of cement sheath during staged fracturing operations [13]. High-density and high-efficiency oil-based drilling fluids should be used to realize perfect combination of flushing and isolation performances. Cares should be taken to promote volumes of flushing and isolation fluids with contact time no less than 10 min. As far as displacement operations are concerned, large volumes of freshwater should be deployed to enhance the returning velocities in annular spaces.

3.5. Optimize fracturing processes to meet the requirements of wellbore integrity

It is necessary to further optimize the compositions and the properties of fracturing fluids to further reduce the impacts of intensive fracturing operations on casings [14–16]. Staged-fracturing processes with large-diameter bridge plugs and fracturing processes with infinite magnitude sliding sleeves should be tested and promoted to minimize risks related to drilling and milling of bridge plugs in coiled tubings.

Fund project

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