Zheng *et al.*
Journal of Engineering and Applied Science (2024) 71:79
https://doi.org/10.1186/s44147-024-00418-6

Journal of Engineering and Applied Science

RESEARCH Open Access

Research on the influence of geological factors on casing stress in casing-in-casing cementing in the horizontal section of shale gas wells

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Abstract

Deep shale gas development has great potential, but the frequent occurrence of shale gas well casing change problems triggered by geological factors seriously restricts deep shale gas development. In order to investigate the influence of geological factors on the casing stress of the cemented casing in the sleeve, a model of formation-cement sheath-double casing assemblage was established, and the influence of three-way geostress and fault slip on the casing stress of the casing-in-casing cementing was investigated by using finite element analysis. The results show the following: the smaller the difference between the vertical geostress and the maximum horizontal geostress is, the lower the equivalent force on the casing is, and when the difference gradually decreases from 20 to 7 MPa, the maximum equivalent force of the inner casing under fracturing condition decreases by 9.4%; the increase of the minimum horizontal geostress leads to the increase of the equivalent force of the inner and outer casing. When the minimum horizontal stress gradually increases from 80 to 90 MPa, the maximum equivalent force of the inner casing under fracturing condition increases by 5.9%. The larger the fault slip and the fault angle, the larger the equivalent force generated on the casing. The shear resistance of the double-layer casing is significantly greater than that of the single-layer casing, with an average increase in fault slip distance that can be withstood of about 45.25% and 40.2% in the no internal pressure and fracturing conditions. The larger the casing steel grade and the thicker the wall thickness, the higher the shear resistance. It is recommended to reduce placing of wells in areas where the difference between the vertical and maximum horizontal ground stresses is large, and at locations where the fault slip angle is large, and to use both higher steel grades and larger wall thicknesses of casing. This research result demonstrates the feasibility of "milling + casing-in-casing" technology in severe casing change wells and also provides useful guidance for the application of this technology in the field.

Keywords: Shale gas wells, Casing change, Casing-in-case cementation, Ground stress, Fault slip

Introduction

The demand for natural gas is gradually increasing around the world, shale gas has become an important source of natural gas, and continuously increasing shale gas production is a pressing issue [1, 2]. Deep shale gas resources are abundant, but after a certain period of development, casing damage occurs in different degrees. The consequences and impacts caused by casing damage are very important for shale gas wells and have become a serious problem restricting shale gas development [3, 4]. The main factors affecting the casing deformation of shale gas horizontal wells include geological, engineering, and cementing factors [5–15], among which geological factors such as geostress and fault slippage cause casing deformation problems, which seriously affect the normal exploitation of shale gas. Li Po et al. [16] took the combined casing-cement sheath-strata structure as the research object and established a finite element model for numerical simulation and concluded that the nonuniform ground stress is an important cause of casing damage. Yu Su et al. [17] studied the effect of casing thickness, nonuniform ground stress, and other factors on casing deformation and concluded that factors such as small casing thickness and large nonuniform ground stress would exacerbate casing stress. Zongyu Lu et al. [18] concluded that shear is the main cause of casing deformation in shale oil and gas wells, and the slip is positively correlated with the fault length and the difference of geostress. Qinglong Lei et al. [19] analyzed the mechanism of casing deformation in shale gas wells, determined that the shear deformation of casing caused by stratum slip is the main factor of casing deformation, and put forward the optimization of the casing deformation management methods such as the optimization of wellbore trajectory. In the same year, they simulated the 8.5-inch wellbore design and carried out casing shear deformation experiments, verifying that casing deformation is shear deformation caused by formation slip [20].

With regard to casing deformation mechanism and casing deformation prevention and control, especially casing deformation in shale gas wells, scholars and engineers at home and abroad have carried out a large number of researches, and all of them believe that nonuniform geostress, geological structure, and other geological factors are one of the main factors affecting casing deformation. However, there is almost no research on the use of “milling + casing-in-casing” technology to control casing deformation in deep shale gas horizontal wells, and it is necessary to conduct research on the influence of casing stress on casing-in-casing cementing in shale gas horizontal wells by geological factors, so as to continue to improve the technology of casing loss wells management. Therefore, for Luzhou shale gas block, where TP140V steel grade casing is used, “milling + casing-in-casing” technology is adopted for channel reconstruction at the site of severe casing loss wells. In this paper, taking the Luzhou shale gas block in South Sichuan as an example, the finite element analysis method is used to establish the formation-cement sheath-double casing combination model, and the influence of geological factors such as three-way geostress and fault slip on the mechanical integrity of casing-in-casing cementing in the horizontal section of shale gas wells is investigated, continuously improve the casing loss well management technology to meet the requirements for subsequent fracturing, reduce the rate of lost sections of deep shale gas, and support the development of deep shale gas on a scale of efficiency, thereby further promoting the development of oil and gas development.

Methods

The focus of this paper is to investigate the influence of the casing stress in casing-in-casing cementing in the horizontal section of shale gas wells by geological factors, and this study is carried out through the following series of steps.

1) Firstly, based on the basic working conditions in the field, a finite element model considering three-way ground stress and fault slip is established.
2) Secondly, the influence of geostress and fault slip on casing stress is investigated.
3) Finally, summarize the influencing factors and put forward relevant suggestions and measures.

Finite element model

According to the well logging data of Luzhou block of South Sichuan shale gas, when the outer casing is completely milled, the set milling length is 2 m. When the outer casing is completely milled, one of the segments will be changed to a single-layer casing, and the horizontal well casing change set milling section schematic diagram is shown in Fig. 1.

The finite element model of double-layer casing-cement sheath-strata combination was established by using finite element software Abaqus. In order to improve the efficiency of finite element calculation, the model needs to be simplified, and the following explanations were made:

1) The casing material is isotropic homogeneous elastic–plastic body, in which the ground layer and the cement sheath follow the Drucker-Prager damage criteria.
2) The cement sheath, formation, and casing in the model have no ring space gap; under the premise of ignoring friction, it is assumed that the faults are tightly fitted.
3) Considering that deep shale gas casing damage mainly occurs in the horizontal well section, in order to eliminate the influence of the boundary effect, take the stratum plane size as 10 times or more of the well diameter size to establish the horizontal wellbore finite element model.

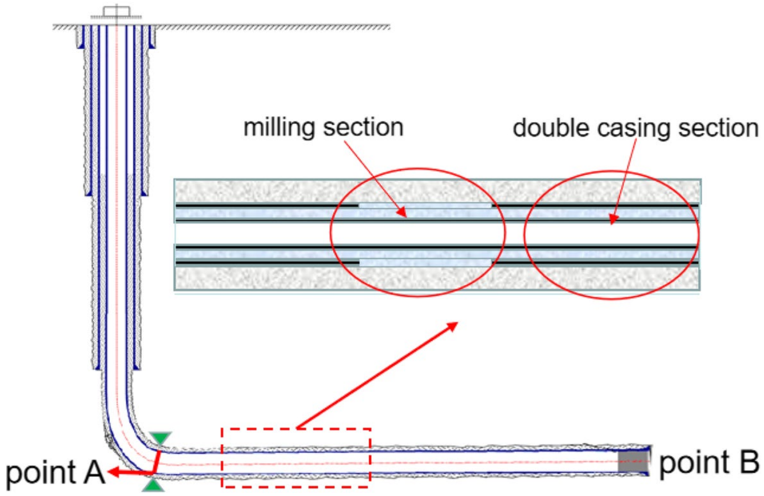


Fig. 1 Schematic diagram of casing grinding and milling in horizontal well section

In the model, the diameter of the borehole is 215.9 mm, the inner casing size is 88.9 mm, and the outer casing size is 139.7 mm, of which the stratigraphic size of the finite element model 1 considering the three-directional stress is 4 m × 4 m × 12 m, and the stratigraphic size of the finite element model 2 considering the fault slip is 3 m × 3 m × 15 m, as shown in Fig. 2. When meshing the model, the overall principle of "sparse outside and dense inside" is adopted, and hexahedral cells are used for meshing. Based on the actual geostress logging data of Luzhou block, the maximum horizontal geostress at the horizontal well section is 92–105 MPa, the minimum horizontal geostress is 80–90 MPa, the vertical geostress is 85–98 MPa, and the pressure P in the casing of the horizontal well is 125 MPa during fracturing.

The finite element model is a horizontal wellbore, with the maximum horizontal geostress σ_x on the x-side, the minimum horizontal geostress σ_y on the y-side, and the vertical geostress σ_h on the z-side, while the inner casing of the inner layer exerts the internal pressure P in the casing of the horizontal well section during fracturing, and the boundary conditions are shown schematically in Fig. 3. The external load of the formation in the fault slip model is finally simplified to the displacement boundary condition of the fault, and the model is divided into two segments, with one segment fixed and one segment slipped along the tangential loading method, as shown in Fig. 4.

According to the rock samples collected at the site of Luzhou block, the performance data measured by triaxial rock mechanics experiments were obtained. In the finite element analysis, the average values of the elastic modulus and Poisson's ratio measurements were taken as the material parameters of the model, and the inner and outer casing steel grades were all TP140V, with a yield strength of 1039 MPa. The relevant parameters are shown in Table 1.

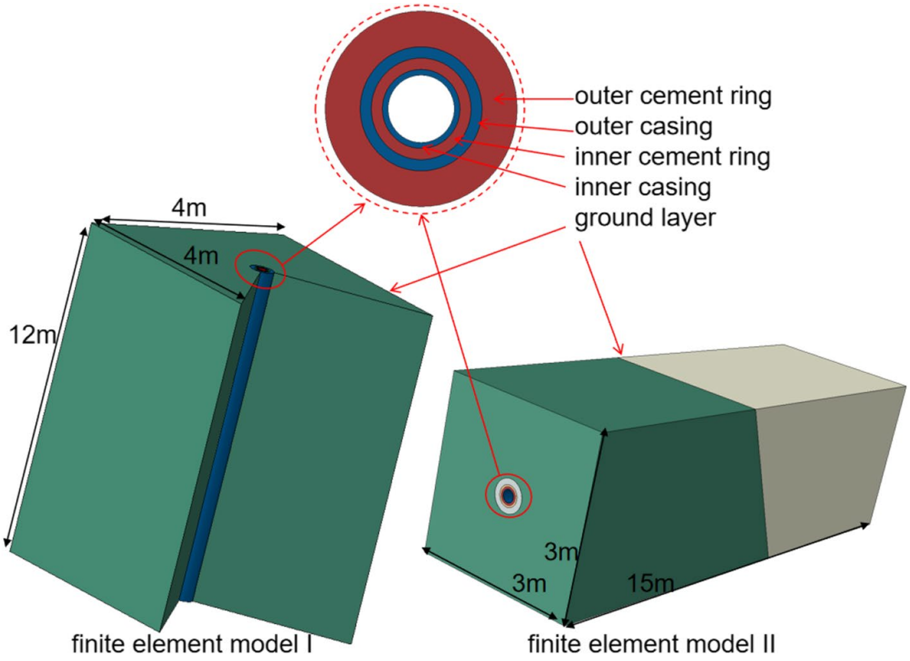


Fig. 2 Finite element model

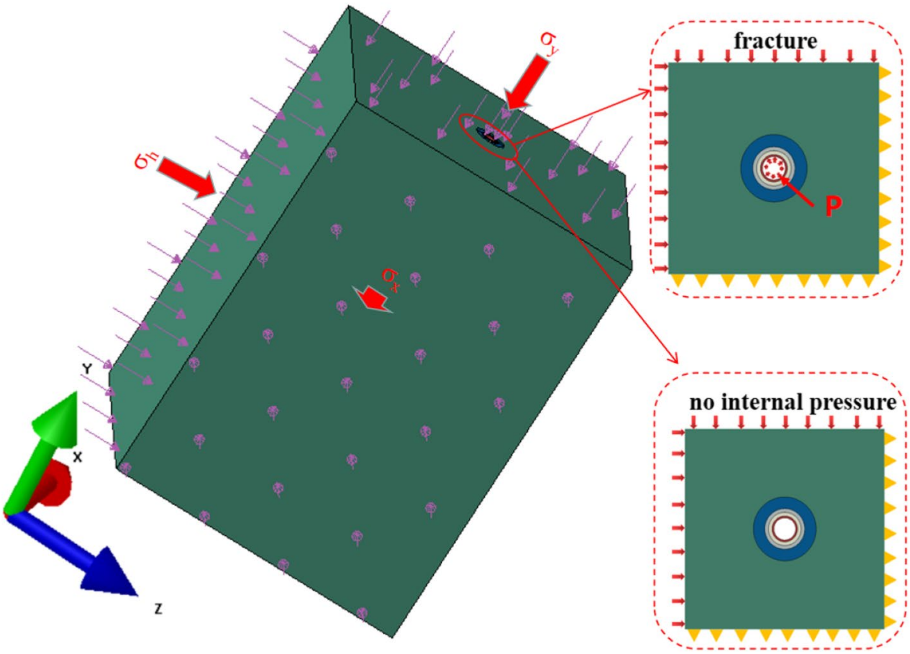


Fig. 3 Schematic boundary conditions of finite element model I considering three-way ground stresses

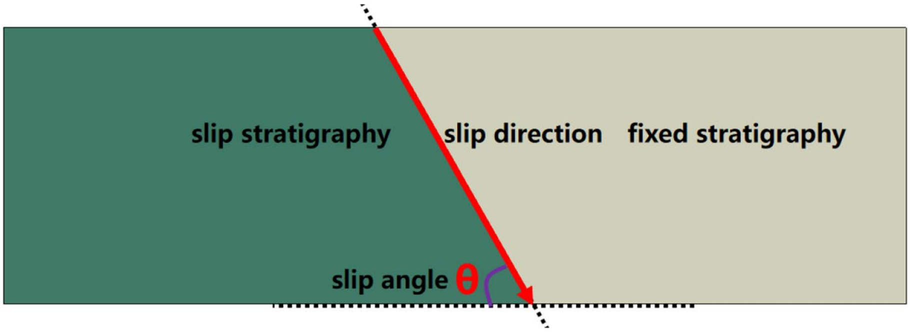


Fig. 4 Schematic boundary conditions of finite element model II considering fault slip

Table 1 Material parameters

Material	Elastic modulus/GPa	Poisson's ratio
Casing	216	0.3
Ground layer	27.75	0.237
Cement sheath	7	0.2

Geostress

The schematic diagram of three-way geostress application in the horizontal section wellbore is shown in Fig. 5, and the influence of geostress on the casing stress of the casing-in-casing cementing is investigated from three aspects.

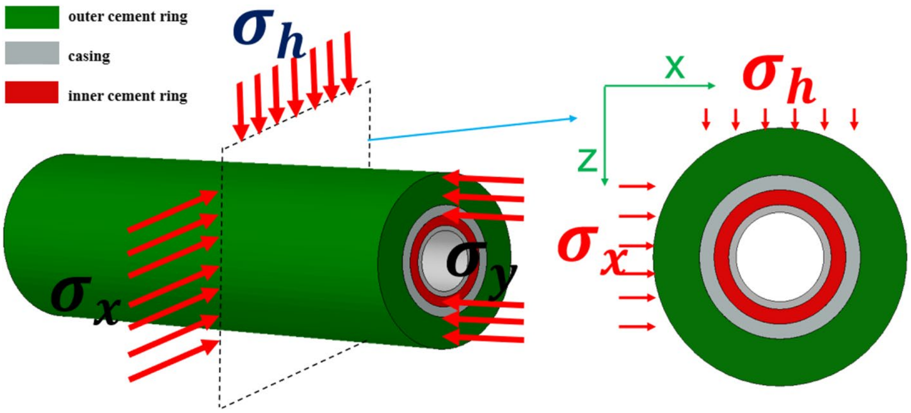


Fig. 5 Schematic diagram of three-way ground stress application in horizontal section wellbore

1) Fix the maximum horizontal geostress of 105 MPa and the minimum horizontal geostress of 90 MPa and analyze the influence of vertical geostress change on casing equivalent stress.
2) Fix the maximum horizontal geopathic stress of 105 MPa and the vertical geopathic stress of 98 MPa and analyze the influence of the change of the minimum horizontal geopathic stress on the equivalent stress of the casing.
3) Fix the minimum horizontal ground stress of 90 MPa and vertical ground stress of 98 MPa and analyze the influence of the change of maximum horizontal ground stress on the equivalent force of the casing.

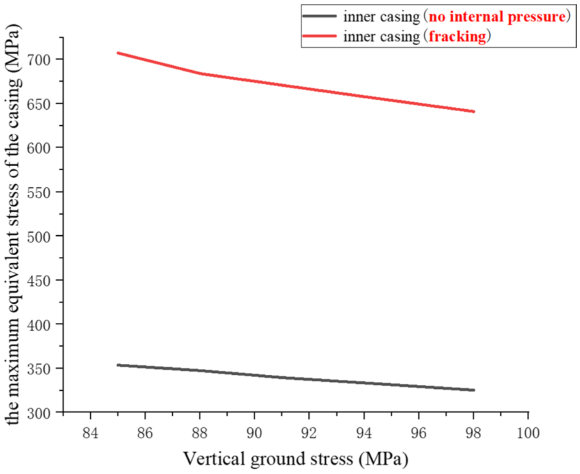
Vertical geostress

Under the condition of fixed cement sheath, stratum, and other working parameters, change the range of vertical ground stress (85–98 MPa) and analyze the maximum equivalent force of inner and outer casing with the change rule of vertical ground stress, and the analysis results are shown in Fig. 6.

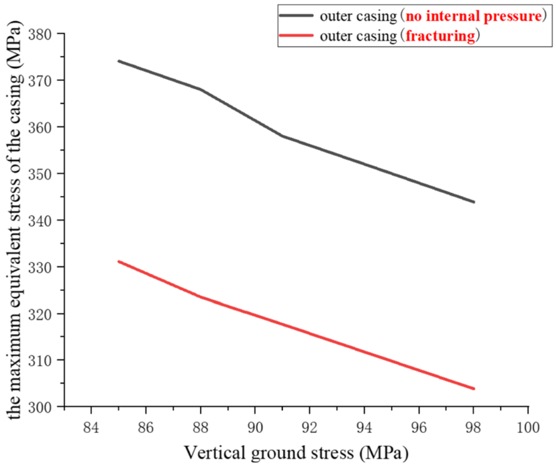
As the vertical geostress gradually increases from 85 to 98 MPa, and its difference with the maximum horizontal geostress gradually decreases from 20 to 7 MPa, the maximum equivalent force of the inner casing decreases by 8% and 9.4% in the no internal pressure and fracturing conditions, respectively, and the maximum equivalent force of the outer casing decreases by 8.1% and 8.2% in the no internal pressure and fracturing conditions, respectively. As the vertical geostress increases, the difference between its value and the maximum horizontal geostress decreases, the influence of nonuniform geostress becomes weaker and weaker, and the equivalent force on the casing gradually decreases.

The larger the difference in the geostress, the casing with originally circular cross section will be squeezed into an ellipse, and stress concentration is generated in the direction of the long axis of the ellipse of the outer casing and the direction of the short axis of the inner casing, respectively, as shown in Fig. 7.

Under the fracturing condition, when the difference between the vertical stress and the maximum horizontal stress reaches 20 MPa, the inner casing of the milling section will



a. the maximum equivalent force of inner casing



b. The maximum equivalent force of outer casing

Fig. 6 The maximum equivalent force of inner and outer casing under different vertical ground stresses. **a** The maximum equivalent force of inner casing. **b** The maximum equivalent force of outer casing

generate a large stress concentration, and the equivalent stress value reaches 765 MPa, as shown in Fig. 8.

Minimum horizontal geostress

Under the condition of fixed cement sheath, stratum, and other working condition parameters, change the size of minimum horizontal ground stress (80–90 MPa) and analyze the maximum equivalent force of inner and outer casing with the change rule of minimum horizontal ground stress, and the analysis results are shown in Fig. 9.

The maximum equivalent force of the inner and outer casing increases with the increase of the minimum horizontal ground stress. When the minimum horizontal ground stress gradually increases from 80 to 90 MPa, the maximum equivalent force of the inner casing increases by 24.6% and 5.9% under no internal pressure and fracturing conditions, respectively, and the maximum equivalent force of the outer casing increases by 17.1% and 27.7% under no internal pressure and fracturing

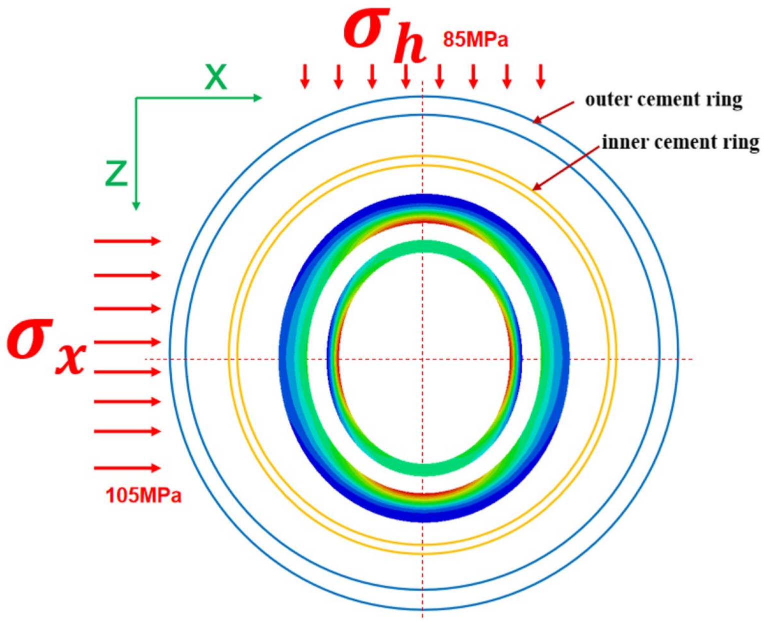


Fig. 7 Cloud diagram of equivalent force of double-layer casing at 20 MPa difference between vertical and maximum horizontal ground stresses

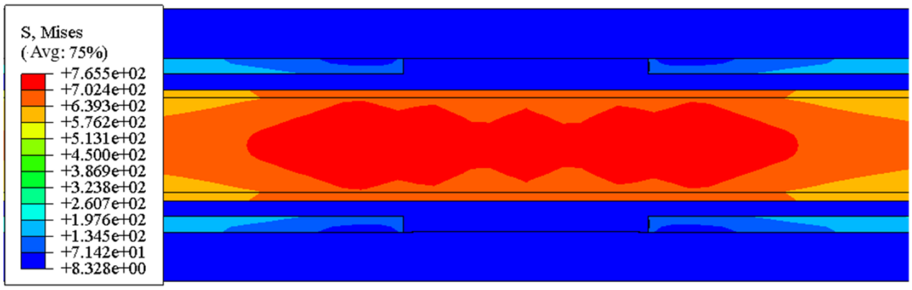
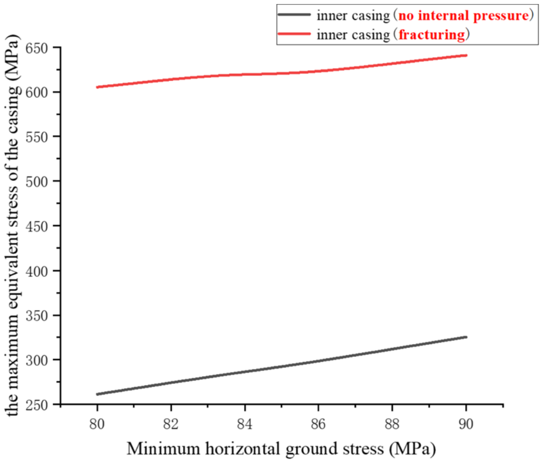


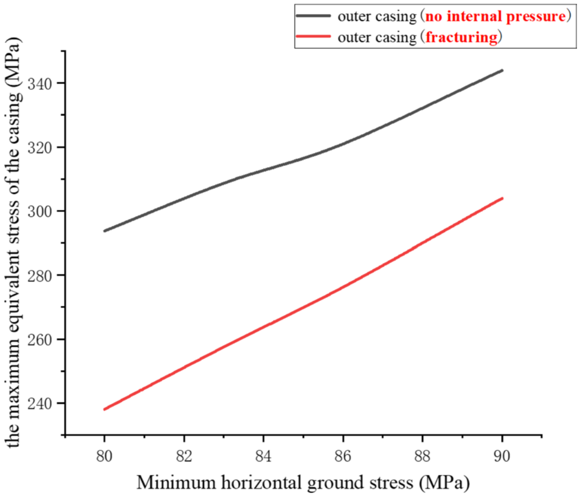
Fig. 8 Equivalent stress cloud of milling section casing (milling length 2 m) under fracturing condition

conditions, respectively. As the minimum horizontal stress increases, it means that the horizontal section casing has to bear more axial loads, which leads to an increase in the equivalent force on the inner and outer casing.

Under the fracturing condition, when the minimum horizontal ground stress reaches the maximum value of 90 MPa, the maximum equivalent force of the inner casing in the milling section is 715.3 MPa, which is significantly larger than the stress value of the double-layer casing section, as shown in Fig. 10. Therefore, after the outer casing is milled, the stress concentration of the inner casing at the milling position will be aggravated, causing the maximum equivalent stress of the inner casing to increase and the risk of casing failure to increase. It is recommended that the inner casing be used casing with high steel grade and large wall thickness.



a. the maximum equivalent force of inner casing



b. the maximum equivalent force of outer casing

Fig. 9 The maximum equivalent force of inner and outer casing under different minimum horizontal ground stresses. **a** The maximum equivalent force of inner casing. **b** The maximum equivalent force of outer casing

Maximum horizontal geostress

Under the condition of fixed cement sheath, stratum, and other working parameters, change the size of maximum horizontal ground stress (92–105 MPa) and analyze the maximum equivalent force of inner and outer casing with the change rule of maximum horizontal ground stress, and the analysis results are shown in Fig. 11.

Under the no internal pressure condition, when the maximum horizontal ground stress increases from 92 to 105 MPa, the maximum equivalent force of the inner and outer casing decreases by 5.8% and 6.4%, respectively. Under the fracturing condition, as the maximum horizontal ground stress increases, the maximum equivalent force of the inner casing decreases and then increases, and the decreasing trend of the maximum equivalent force of the outer casing gradually slows down. Under the fracturing condition, as the maximum

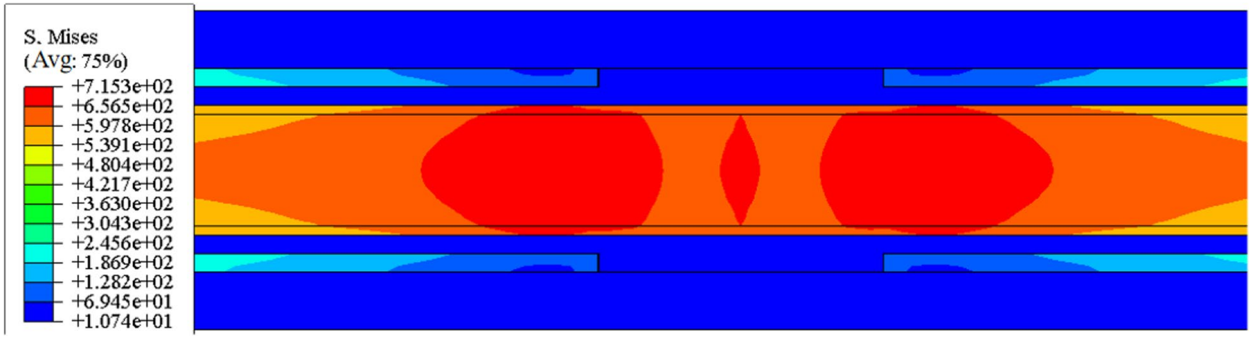
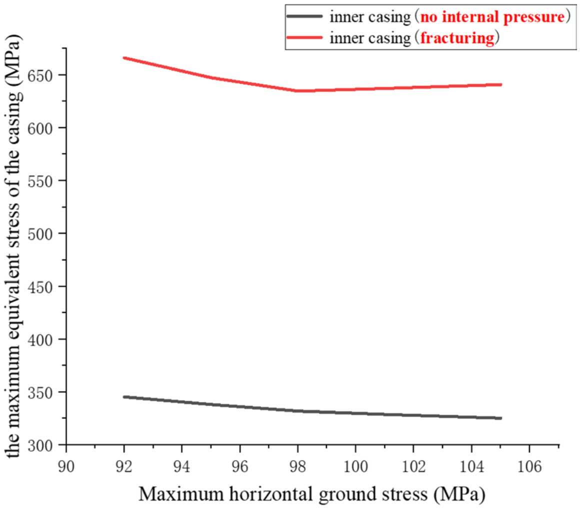
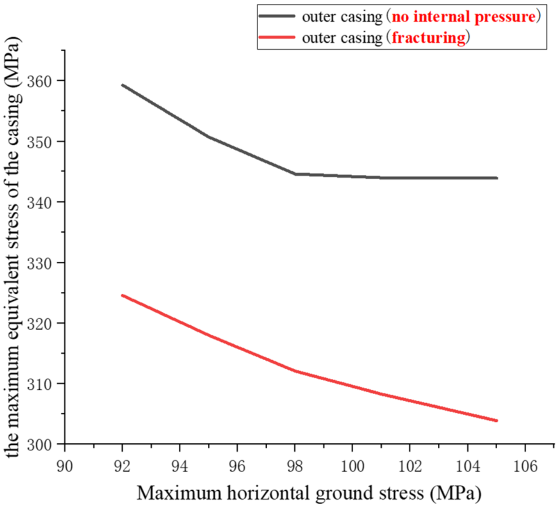


Fig. 10 Equivalent force cloud of milling section casing (milling length 2 m) under fracturing condition



a. the maximum equivalent force of inner casing



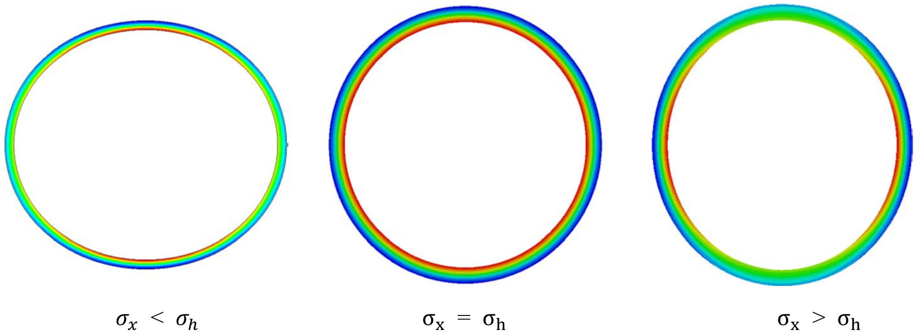
b. the maximum equivalent force of outer casing

Fig. 11 The maximum equivalent force of inner and outer casing under different maximum horizontal ground stresses. **a** The maximum equivalent force of inner casing. **b** The maximum equivalent force of outer casing

horizontal stress increases, the maximum equivalent force of the inner casing decreases and then increases; when $\sigma_x < \sigma_h$ or $\sigma_x > \sigma_h$, the stress concentration occurs in the short-axis direction of the inner casing; when $\sigma_x = \sigma_h$, the stress value of the inner casing is minimum, and the stress is more uniform, as shown in Fig. 12.

Under the fracturing condition, when σ_x is equal to the minimum value of 92 MPa, the maximum equivalent stress of the inner casing in the milling section is 740.2 MPa, which is significantly larger than that of the double-layer casing section, as shown in Fig. 13.

$\sigma_x < \sigma_h$ $\sigma_x = \sigma_h$ $\sigma_x > \sigma_h$



$\sigma_x < \sigma_h$ $\sigma_x = \sigma_h$ $\sigma_x > \sigma_h$

Fig. 12 Deformation cloud of equivalent force of inner casing under different maximum horizontal ground stresses

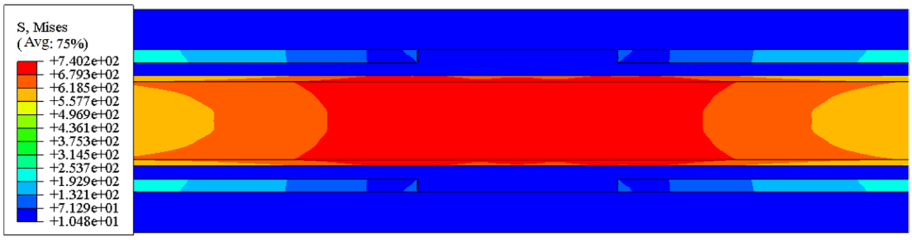


Fig. 13 Equivalent stress cloud of milling section (milling length 2 m) under fracturing condition

Fault slip

The numerical model of fault slip is established by using finite element software to study the ultimate slip amount that single-layer casing and double-layer casing can withstand under different angles of fault slip in the horizontal well section after the casing is milled. When the wellbore passes through the middle of the sliding fault, the casing cannot resist the deformation of the formation due to the huge volume difference between the formation and the casing, so the casing will be shear deformed together with the fault. In order to evaluate the shear capacity of single-layer casing and double-layer combined casing in the milling area, the research is carried out from the following three aspects:

1) The relationship between equivalent force and slip of single-layer casing in milling area under different fault angles (the fault angles are set to 15, 30, 45, 60, 75, and 90° respectively).
2) Relationship between equivalent force and slip of double-layer combined casing under different fault angles (the fault angles are set to 15, 30, 45, 60, 75, and 90° respectively).
3) Relationship between equivalent stress slip for inner casing of different steel grades and wall thicknesses (with fault angle of 60° as an example)

Impact of fault slip on single-layer casing in milling areas

Fault slip causes the formation to squeeze the casing, resulting in shear deformation of the casing. Under the conditions of fixed cement sheath, formation, and other working

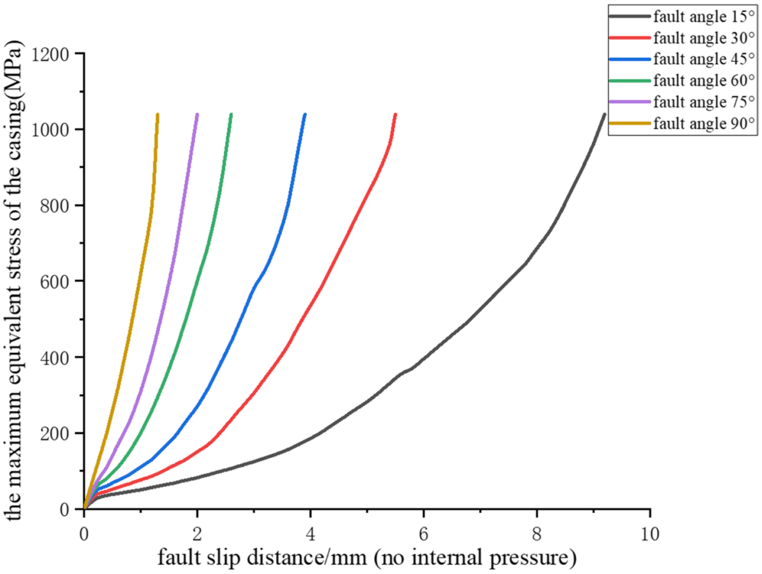


Fig. 14 Stress-slip relationship of single-layer casing at different fault angles (no internal pressure condition)

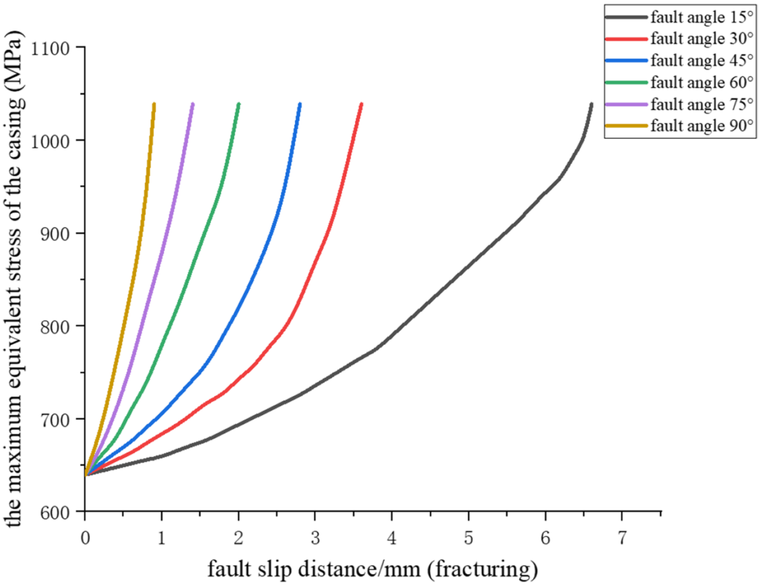


Fig. 15 Stress-slip relationship of single-layer casing at different fault angles (fracturing condition)

parameters, the size of the fault angle is changed, and the change rule of the slip amount of single-layer casing in milling section with the fault angle is analyzed in the conditions of no internal pressure and fracturing, respectively. The stress-slip relationships of single-layer casing under different fault angles are shown in Figs. 14 and 15.

Under the fracturing condition, the inner casing bears both the internal pressure and the external pressure, so the two-way shear effect will be formed on the slip surface, so that fault slip distance that the casing can withstand when yielding will be lower than that under the condition of no internal pressure. The amount of slip required to reach the yield strength of the casing for a single layer of casing under fracturing conditions is on average about 29% lower than under no internal pressure conditions. As the angle of the fault increases, the fault slip distance that the single-layer casing can withstand when yielding decreases; the larger the slip angle is, the greater the stress on the casing under the same fault slip distance, i.e., if the casing is subjected to the same stress, the larger the angle of the fault, and the smaller the fault slip distance required.

The energy of the sliding fault is huge, and with the huge volume difference between the formation and the casing, the casing is unable to resist the deformation of the formation, so the casing produces shear deformation at the junction of the fault and the wellbore, as shown in Fig. 16.

Impact of fault slip on double casing

Under the conditions of fixed cement sheath, stratum, and other working parameters, the size of the fault angle is changed to analyze the change rule of the slip amount of the double-layer casing with the fault angle under the no-inner-pressure and fracturing working conditions, respectively. The stress-slip relationships of the double-layer casing under different fault angles are shown in Figs. 17 and 18.

The slip required to reach the yield strength of the casing for a single layer of casing in the milling section under fracturing conditions has decreased by about 29% on average compared with that under no internal pressure conditions. The slip required to reach the yield strength of the double-layer casing under fracturing conditions decreased by about 51% on average compared to the no-inner-pressure condition. The amount of slip that the double-layer combination casing can withstand when yielding is significantly higher than that of the single-layer casing, with an average increase in slip of approximately 45.25% in the no-intra-pressure condition and an average increase of approximately 40.2% in the fracturing condition compared to the single-layer casing.

Although the double-layer casing can improve the slip shear resistance to a certain extent, it still cannot resist the huge energy of formation slip, and it also produces shear deformation at the junction of the fault and the wellbore, as shown in Fig. 19.

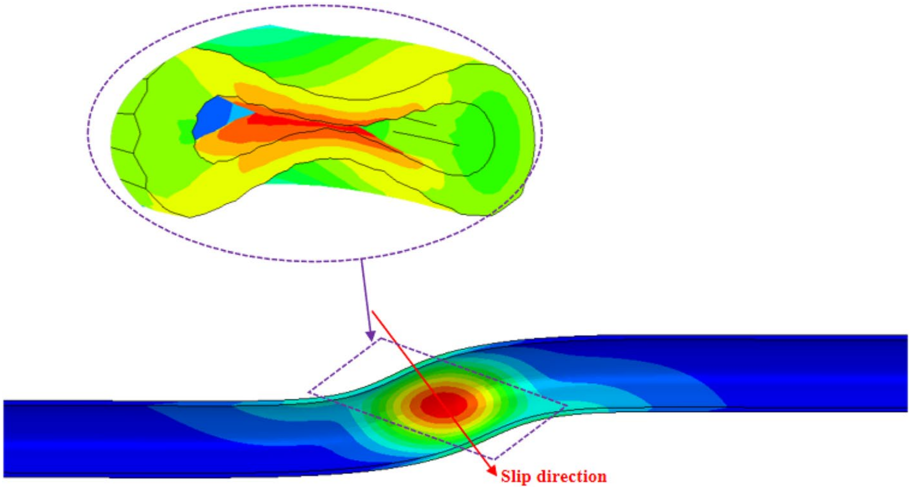


Fig. 16 Cloud view of shear deformation of single-layer casing in milling areas

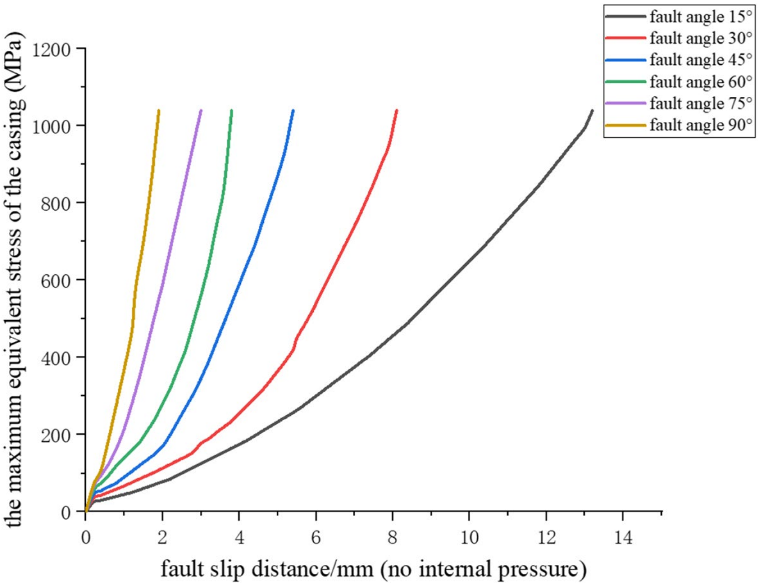


Fig. 17 Stress-slip relationship of double-layer casing under different fault angles (no internal pressure condition)

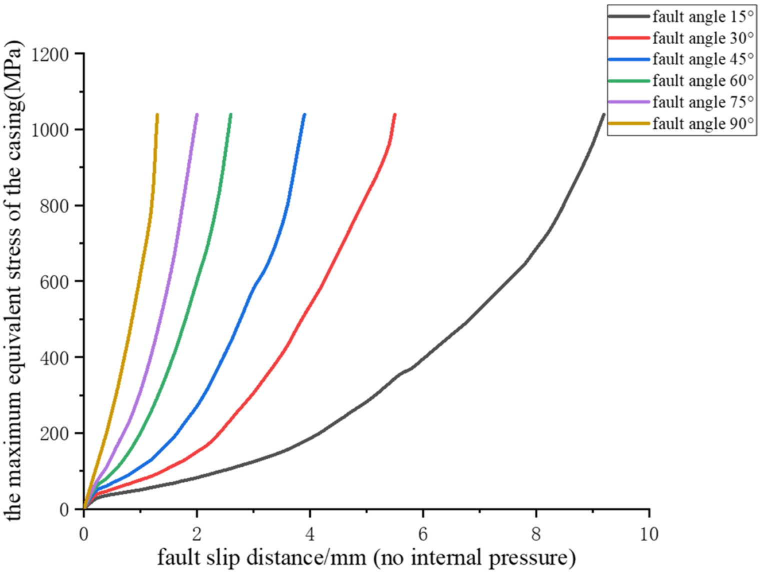


Fig. 18 Stress-slip relationship of double-layer casing under different fault angles (fracturing condition)

Anti-slip shear capacity of double-layer combined casing with different steel grades and wall thicknesses

Under the condition of fixed cement sheath, stratum, and other working parameters, set the fault angle as 60°, change the steel grade and wall thickness of inner casing, and analyze the change rule of slip amount of double-layer casing with steel grade and wall thickness under no internal pressure and fracturing working condition respectively. The

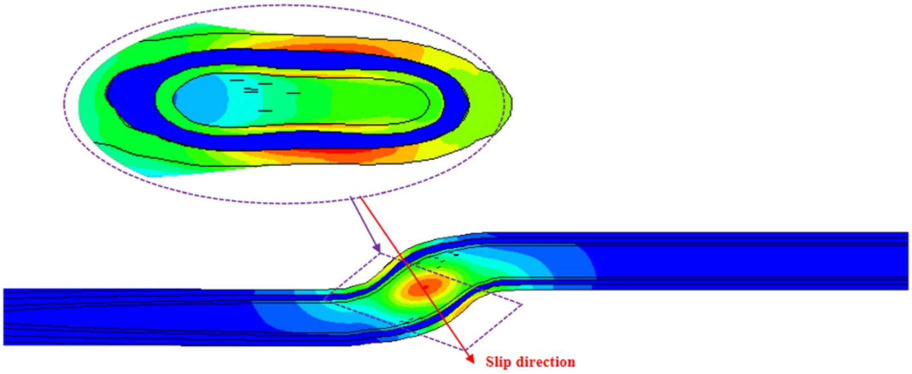


Fig. 19 Cloud diagram of shear deformation of double-layer casing

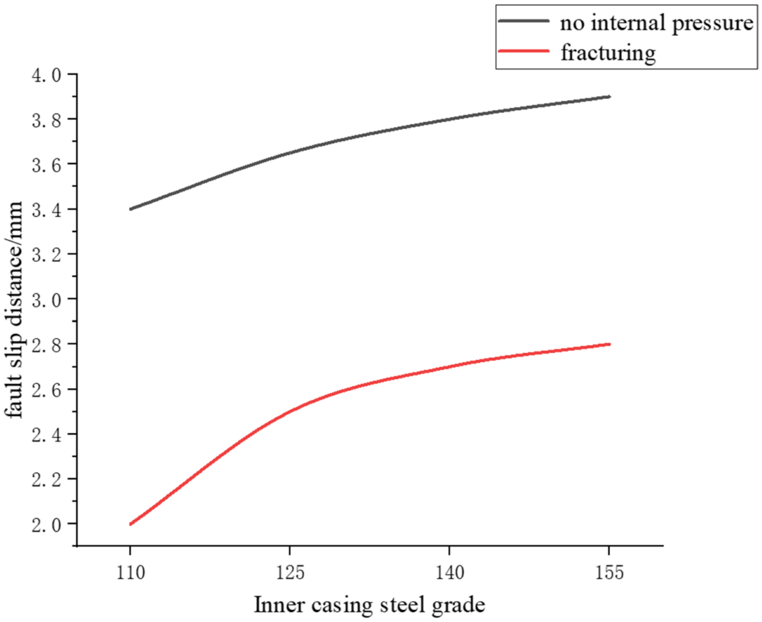


Fig. 20 Shear slip that can be sustained by inner casing of different steel grades at yielding of double casing

slip amount of double-layer casing yielding at each angle of the fault is shown in Figs. 20 and 21.

The larger the steel grade of the casing, the thicker the wall thickness, and the stronger the shear capacity it can withstand. Under the condition of no internal pressure, the slip shear capacity of 125 steel grade increases by 7.4%, 140 steel grade increases by 11.2%, and 155 steel grade increases by 14.7% compared with 110 steel grade; under the condition of fracturing, the slip shear capacity of 125 steel grade increases by 25%, 140 steel grade increases by 35%, and 155 steel grade increases by 40% compared with 110 steel grade. Under no internal pressure condition, the slip shear capacity of 6.45-mm wall thickness increased by 5.6%, and 7.34-mm wall thickness increased by 8.3% compared to 5.49-mm wall thickness; under fracturing

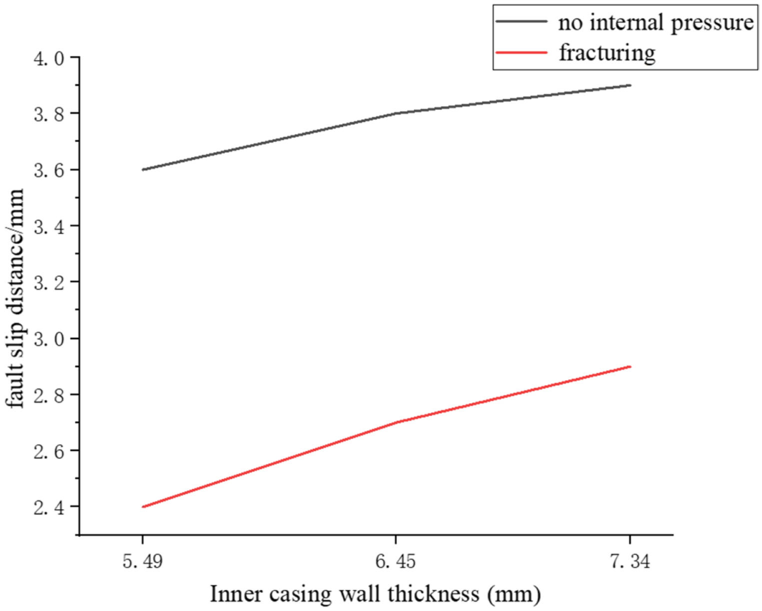


Fig. 21 Shear slip that can be sustained by inner casing with different wall thicknesses at yielding of double casing

condition, the slip shear capacity of 6.45-mm wall thickness increased by 12.5%, and 7.34-mm wall thickness increased by 20.8% compared to 5.49-mm wall thickness.

Conclusions

1) Geostress has a significant effect on casing stress. The smaller the difference between vertical stress and maximum horizontal stress, the weaker and weaker the influence of nonuniform geostress. It is recommended to reduce placing of wells in the area where the difference between vertical stress and maximum horizontal stress is larger, and at the same time, to improve the steel grade and wall thickness of the casing.
2) The larger the fault slip and fault angle are, the larger the equivalent force on the casing is. It is recommended that the wells should not be located at the position with larger fault slip angle, so as to avoid the casing to bear huge shear force.
3) In the process of shale gas extraction, detailed investigation of underground fault development in the geological design stage, and according to the geological characteristics of different wells to optimize drilling, try to avoid faults; good borehole trajectory is of great significance to reduce the damage to the casing, and can effectively avoid the shear deformation of the casing caused by fault slippage, in order to reduce the probability of failure of horizontal wells.

Abbreviations

σ_x	The maximum horizontal geostress
σ_y	The minimum horizontal geostress
σ_h	The vertical geostress
P	The internal pressure

Acknowledgements
Not applicable

Authors' contributions
YZZ helped with the writing of the manuscript, provided technical guidance, and was a major contributor in writing the manuscript. JZ, XHH, and ZLL collected and analyzed the data and wrote the manuscript. ZWZ, ZMG, YH, and LH provided ideas and guidance on the manuscript. YC and YX edited the manuscript and provided some references and provided language modification and polishing for this article. All authors read and approved the manuscript.

Funding
This research article was funded by the major scientific and technological project of PetroChina Southwest Oil and Gas Field Company, "Research on the mechanism of casing change and countermeasures for prevention and control of deep shale gas wells" (No. 20220304-20).

Availability of data and materials
All materials and data used were obtained at the Engineering Technology Research Institute, PetroChina Southwest Oil and Gas Field Company. The datasets used and analyzed in this study are available upon request from the corresponding author.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All the authors have agreed to publish this article.

Competing interests
The authors declare that they have no competing interests.

Received: 16 January 2024 Accepted: 13 March 2024

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