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Optimization of Casing Design Parameters to Mitigate Casing Failure Caused by Formation Slippage

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Abstract: There has been lack of work efforts on how to optimize cementing and completing parameters in order to prevent casing failure induced by formation slippage in pertroleum industry scope. Once the weak plane fails, the formation will become easily undertaken slippage across a large area along its interface. The plenty of horizontal planes of weakness in reservoir formations, as reported for a number of oilfields, can easily undertaken slippage once it fails. To address the problem, three-dimensional finite element models were established by taking into considerations the elastoplastic mechanical characteristics of both the casing and the near-wellbore rock. Two types of casing impairment scenarios were considered: Casing collapse (that causes tubing stuck in the well) and complete casing shear-off. In this study, the critical slip displacement of casing shear damage under both cemented and un-cemented conditions was calculated, and the critical displacement of casing with various wall thicknesses and steel grades was compared. A new cementing practice for the Daqing oilfield was then proposed by optimizing casing parameters according to API standards, and a new research method was also put forward by proposing new casing materials to effectively mitigate casing failure caused by formation slippage for the future. Modeling results indicate that the stress and deformation associated with casing in the un-cemented condition is more diffused and the critical slippage displacement is larger than that in the cemented condition. Therefore, the un-cemented condition is more effective in preventing casing shear failure and easier for casing repair, for the case of casing damage caused by formation shear slippage. Casing elongation is the key parameter of casing shear failure in the un-cemented condition. Lower grade casing exhibits a larger critical slippage displacement because of its higher elongation capacity under stress. Casing with lower grade and smaller thickness provides more advantages in preventing casing damage in formations abundant with horizontal weak layers. If the elongation of casing can be largely improved, the critical displacement value can be increased by 21.40%. Higher grade and thicker casing is adapted for mitigate casing failure caused by formation slippage.

Keywords: Finite element, casing design, formation slippage, casing failure.

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1 Introduction

Large area of horizontal planes of weakness layer is contained in some of the reservoir or the upper layer of reservoir [Bruno (1992); Hamilton, Mailer and Prins (1992); Denney (2003); Furui, Fuh and Morita (2012); Simpson, Stroisz, Bauer et al. (2014)], especially shale layers. It will induce large area casing failure once the weak layer fails and slip. Lots of casing damage resulted in the formation slippage [Maurice, Michael and John (2001); Li, Mitchum, Bruno et al. (2003); Han, Khan and Ansari (2012)]. In recent years, Zhu et al. [Zhu, Deng, Zhao et al. (2014); Adams, Mitchell, Eustes et al. (2017); Wang, Han, Li et al. (2017)] discovered casing damage caused by shale fracturing process, which is also confirmed to be caused by formation slip.

This phenomenon is commonly occur Daqing oilfield, China as studied by Liu et al. [Liu, Liu, Zhou et al. (2006); Hong, Maurice and Xu (2006); Liu, Yan, Xue et al. (2005)]. The Nen'er bottom datum bed located 60 m to 80 m above the pay zone in Daqing oilfield. The lithology of datum bed is oil shale which has a very large area and about thickness of 10 m. Inside of the shale zone, there are plenty layer of fossil which result in Calcium content increase. The high Calcium content layer is fragile and easily broken. Many horizontal weak layers formed by the influence of fossil. The shearing strength of shale zone is lower than that in all other formation. A large number of tests proved that the weak layer has failed in parts of the block, and the slippage of weakness has formed.

Water injection over long period of time in oilfield led the reservoir pressure unequally among blocks, and the reservoir unequally caused by the pressure difference. Reservoir deformation induces all the upper formations deform, and cause the upper and lower formation of weak layer horizontally slips. When the slippage degree reaches its limitation the casing will failure. According to uncompleted statistics, 40% to 50% casing failure is caused by weak layer slippage at shale zone in recent decade.

A part of the wells leave the shale zone un-cemented by set a cement surface controller under it in Daqing oilfield reported by Li et al. [Li, Liu, Yao et al. (2014)] as shown in Fig. 1.

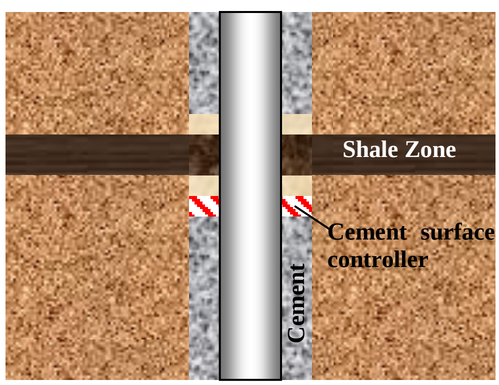


Figure 1: Shale zone un-cemented well

There is no cement at Nen'er bottom shale zone by using this technology. But the concept and work about shale zone should cement or not in each branch company is different and not been unified yet. In addition, the critical casing damage displacement is influenced by casing wall thickness and steel grade. However, there has been lack of study affords on it.

In previous casing failure study, the casing and well bore or cement was commonly assumed directly contact, such as Huang et al. [Huang, Liu and Yang (2009); Wang, Wu and Li (2004)]. There is lack of research on the condition of the un-cemented well shearing. This paper considered both cemented and un-cemented models, established finite element models separately by using Comsol Mutiphysics and analyzed casing, cement and near-wellbore rock elastoplasticity deformation characteristic in the progress of weak layer slippage, and the more effective cementing method was analyzed from the view of mechanics. Critical casing failure limitation of various casing thickness and steel grade was calculated. The wall thickness and steel grade of API standers casing was optimized to mitigate or delay casing failure caused by weak layer formation slippage.

2 Finite element models

2.1 Geometric models

According to the symmetrical characteristic of the geometry and the force, 1/2 symmetrical models with 1 m broadwise length were established. Assuming the weak layer has been failed, the formations were divided into upper and lower side with both 0.5 m highnesses. The wellbore diameters are 0.2 m and the casing outer diameter was 139.7 mm in both cemented and un-cemented model.

In un-cemented model, there is no force between formations and casing when the slippage displacement less than the distance between casing and well bore. So

$s_s=s-(d_w-D_c)$

where s_s is the formation-shear-casing displacement (that defining the place where the weak layer start to shear casing as the initial point, it is the slippage displacement after initial point), mm; s is the weak layer slippage displacement (that defining the initial point is the well formed, it is the slip displacement after initial point), mm; d_w is the well bore diameter, mm; D_c is outer diameter of casing, mm.

As a contrast in cemented model, once the upper and lower formation slips by outer stress after the weak layer failed, the stress will transmit to the cement and casing. The formation-shear-casing displacement equals the weak layer slippage displacement. So

$s_s=s$.

For the cemented model, the initial point is the casing in the middle of the wellbore, where s=0. For the uncemented model, the initial situation started from the casing shearing location, where $s=(d_w-D_c)$. The casing deformation is large in the progress of casing shear. To ensure the accuracy, subdivision the casing finite element meshes to minimize the error as studied by Zhang [Zhang (2001)]. As the stress focused near the shear interface, the meshes of casing, cement and formations near the weak plane was refined. The established meshes division results are shown in Fig. 2 and Fig. 3.

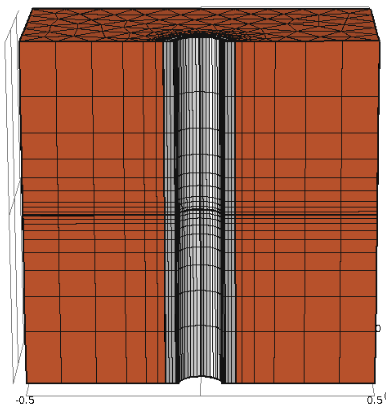


Figure 2: Cemented model mesh division

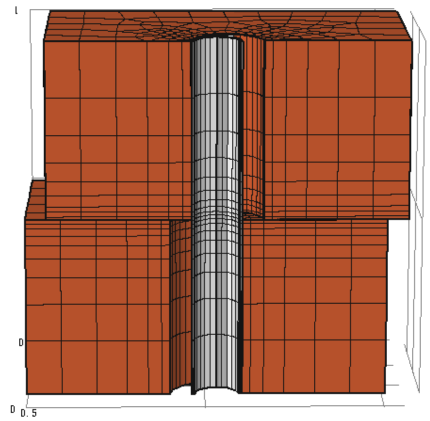


Figure 3: Un-cemented model mesh division

The prescribed displacement of x normal direction of the two near-wellbore rocks in upper formation was set equals s_c, and the prescribed displacement of other sidewalls were set to 0.

2.2 Material mechanics parameters

In the oilfield, the casing is not determined failure occurring small plastic deformation. Whenever the casing keeps its integrity and the deformation is not able to affect implement, the casing will consider as un-failure. The casing shear failure found in the well was serious plastic deformation undertaken on the casings. So the finite element calculation models need to take into considerations the elastoplastic mechanical characteristic after casing yield. When the stress in the casing exceeds the yield strength, it will enter into the plastic deformation section. According to the bilinear material model [Liu (1988)], the constitutional equation of hardening material such as alloy steel can be described as

$$\sigma = \begin{cases} \boldsymbol{E}\varepsilon & (\varepsilon \le \varepsilon_s) \\ \sigma_s + \boldsymbol{E}_l(\varepsilon - \varepsilon_s) & (\varepsilon > \varepsilon_s) \end{cases}.$$

where σ is casing stress, MPa; σ_s is casing yield stress, MPa; E is Young's modulus in linear elastic stage, MPa; E_l is modulus in harden stage, MPa; ε is casing strain, dimensionless and ε_s is casing strain when casing yield, dimensionless.

Table 1: The casing mechanics parameters

Steel grade	Young's modulus (GPa)	Poisson's ratio	Yield stress (MPa)	Tensile strength (MPa)	Modulus in harden stage (MPa)	Elongation (%)
J55	206	0.29	379	517	579.4	24
N80	206	0.29	552	689	731.2	19
P110	206	0.29	759	862	710.6	15

Strength and elongation of various steel grade reference API Spec 5CT. Modulus in harden stage of casings were calculated by Young's modulus, elongation, yield stress and tensile strength. Casing parameters is shown in Tab. 1.

The mechanics parameters of the cement mantle in cemented model referred to the average value of Daqing oilfield. The cement mantle Young's modulus took 40 GPa, the Poisson's ratio took 0.23, the inner friction angle took 30° and the uniaxial compressive strength takes 40 MPa. The mechanics parameters of the near-well bore rock took the average test results of previous. The Young's modulus of shale zone rock took 12.8 GPa, the Poisson's ratio took 0.28, the inner friction angle took 30° and the adhesive force took 15.9 MPa. The cement and the near-wellbore rock beside the interface of the weak planes might also break in the progress of formation slippage, and therefore the Mohr-Coulomb criterion was applied to calculate the extent of damage of cement and rock in the finite element model.

3 The critical impairment scenarios of casings

There are two impairment scenarios of casings: (1) Casing collapse. Run through casing diameter is less than collar outside diameter and causes tubing stuck in the well, shown in Fig. 4. The critical impairment scenario of run through casing is the tube collar outside diameter; (2) Casing shear-off, shown in Fig. 5. The fundamental reason of causes shear-off is the casing stretched near the interface. When the Von Mises stress greater than the tensile strength, the fracture formed in the casing, and the casing start to break.

Figure 4: Casing collapse

Figure 5: Casing shear-off

In the progress of casing failure, the minimum run through diameter located at the shearing interface where the casing deformation symmetrically. The run through casing diameter is

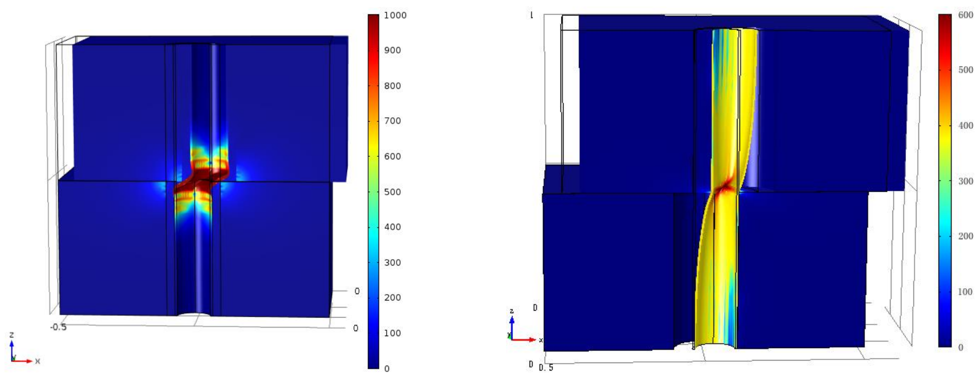
$$d_e=D_c-2(t-\Delta t)-s_s+2s_w$$

where d_e is run through casing diameter, mm; t is the thickness of casing, mm; Δt is the decrement of thickness, mm; s_w is deformation of single side wellbore, mm.

With the slippage displacement increasing, the run through casing diameter will become smaller, and the Von Mises stress will increase. When anyone of impairment scenarios reaches its limitation, the casing will be failure. Defining the formation slippage displacement at the critical point as critical casing failure slippage displacement, and define the formation-shear-casing displacement at the critical point as critical casing sheared displacement. Of cause, the critical casing failure slippage displacement equals the critical casing sheared displacement in the cemented model.

4 Optimization of well completion method

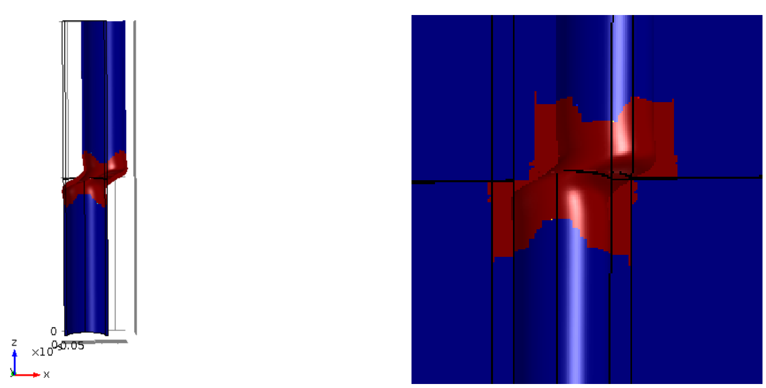
The only difference between cement and un-cement model is the cement. Finite element calculations indicate the cement has a great influence on the casing and rock in the slippage progress. Assuming the range of formation-shear-casing displacement is 50 mm. The stress and deformation of the J55 casing with a wall thickness 6.20 mm, cement and near-wellbore rock in both cemented and un-cemented model were calculated by the finite element shown in Fig. 6.



(a) Cemented model (b) Un-cemented model

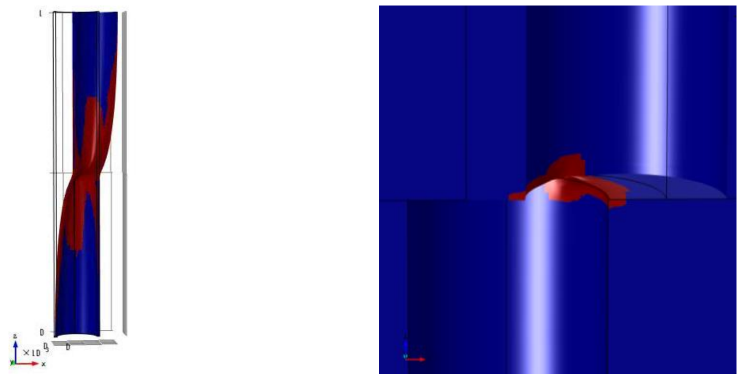
Figure 6: Von Mises stress and deformation of casing, cement and formation

The stress is concentrate near the slippage layer in the two models. The stress on the casing is much greater than that in the near-wellbore rock. The stress and deformation associated with casing in cemented model is more diffused. The more casing deformed, the more influence on the implement, and the casing is also harder to repair. The plastic deformation zones when the formation-shear-casing displacement reach 50 mm in two models is shown in Fig. 7.



(a) Plastic deformation zone of casing in cemented model

(b) Plastic deformation zone of cement and near-wellbore rock in cemented model



(c) Plastic deformation zone of casing in un-cemented model

(d) Plastic deformation zone of near-wellbore rock in cemented model

Figure 7: Plastic deformation zones of casing, cement and near-wellbore rock

The reaction force of casing and cement was appeared when formation slipped. The reaction force of both cemented and un-cemented model is shown in Fig. 8.

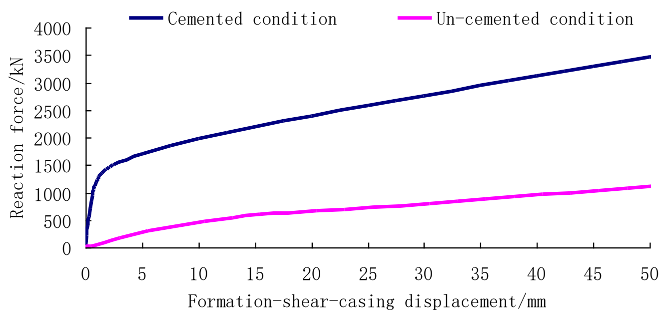


Figure 8: The reaction force in two models

In the progress of formation slippage in two cemented models, the reaction force suffer by near-wellbore rock is mostly like a two-stage polyline. The casing and the cement entered into yield stage when formations slip a small distance and the reaction force increase when the slippage displacement increases. As the effect of the cement, the reaction force in cemented model is greater than that in un-cemented model.

However, the reaction force is far away smaller than the motive force of formation slippage. When the planes of weakness slips, the motive force need for greater than the interface friction at least. Assuming that the depth of shale zone is 700 m, density of overburden is 2200 kg/m^3, average area of a single well (that is the reciprocal of the number of wells in a unit area) is 1600 m^2 per well, and the coefficient of friction is 0.1. The calculated friction is 2.41×10^6 kN which is about 600 times larger than the reaction force of casing. So the casing is forced to deformation when formation slippage occurred. However, the formation will not slip without stopping. The motive slippage force decreases when formation slips, and formation will stop slipping when the motive force too small.

There lives a space between casing and wellbore rock in un-cemented model, which result in the formation shearing casing when the formation slippage displacement larger than the space. As a contract in cement model, the casing is greatly deformed at that slippage displacement. So leave the shale zone un-cemented can effectively mitigate casing damage.

5 Optimization of casing parameters

The outer diameter of casing is selected according to the need of oil production and often can not be easily changed. The optimizations of casing parameters focus on the thickness of casing and steel grade. Finite element model calculations method is used to optimize casing parameters. As studied about cementing method, the un-cemented model provides more advantage in prevent casing failure, so the cemented method is not considered below.

5.1 Optimization of casing thickness

At the view of run though casing diameter, the thicker casing wall is, the greater deformation of near-well bore will, and the slower of run though casing diameter changes. But at the meantime, the thickness itself decreases the initial value of casing inside diameter. Results indicate the increase of wellbore deformation (s_w) and thickness decrement (Δt) is much less than the increase of wall thickness. The increase of casing wall thickness cannot effectively delay run though casing diameter changes.

Casing with an outer diameter of 139.7 mm thickness is commonly used in Daqing oilfield. The wall thickness is 6.20 mm, 6.98 mm, 7.72 mm, 9.17 mm and 10.54 mm in API standers. Fig. 9 shows the result of run though casing diameter of various casing thickness against formation-shear-casing displacement.

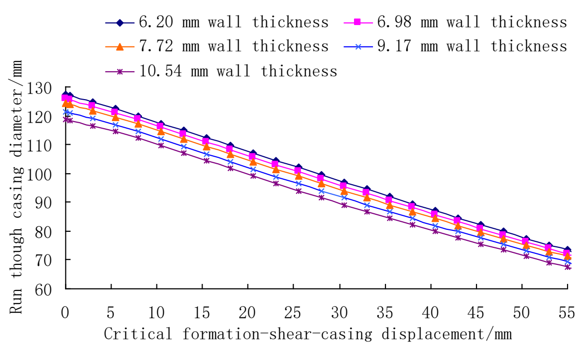


Figure 9: Run though casing diameter of different casing thickness against formation-shear-casing displacement

Result indicate run though diameter almost linearly decreases when slippage displacement increases. The allied tubing collar outer diameter of casing with a wall thickness of 139.7 mm is commonly 73.02 mm. The wellbore deformation (s_w) and thickness decrement (Δt) is 2.21 mm and 0.17 mm separately, and it is too small to contract with the critical value.

At the view of maximum Von Mises stress, although the increase of wall thickness can increase critical shearing stress, the motive slippage force is much larger than the ability of casing to resist it. The increasing wall thickness increases the difference of outer and inner diameter instead, which result in stress concentration seriously. Modeling results indicate then thin casing has a small maximum when formation slipping and the critical casing sheared displacement is larger. Fig. 10 shows the maximum Von Mises stress of J55 casing with a various wall thickness.

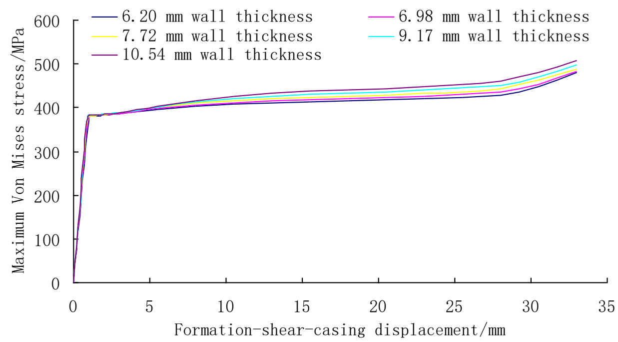


Figure 10: Maximum Von Mises stress of various casing thickness against formation-shear-casing displacement

The Maximum Mises stresses grow rapidity at the prime, and grow slower after the stress over the yield stress. The difference of Mises stresses in each thickness is small, and the thicker casing has the maximum stress, which means shear-off most easily.

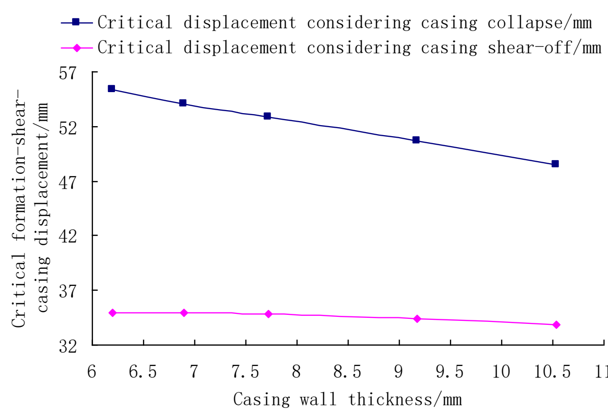


Figure 11: Casing thickness against critical casing sheared displacement

Combining the with two impairment scenarios, the value of critical displacement of casing collapse are among 45 mm to 50 mm while the value of casing shear-off are nearly 35 mm. So the casing will shear-off first caused by formation slippage. Lots of well tests shown that all the detected casings collapse were proved casing shear-off at last, and two failure scenarios including shear-off and shearing deformation was detected in the tube un-stunk wells. These tests can more or less prove that the casing will shear-off first when sheared in the formation slippage situations. The critical casing sheared displacement of two impairment scenarios in various casing wall thickness is shown in Fig. 11.

The critical casing sheared displacement of 6.20 mm thickness casing is 34.99 mm while the critical displacement is 33.87 mm of the casing with a 10.54 thickness. It means that the casing with a thin wall is safer, although the critical is mostly the same, and the thin casing has a low cost. So, the thick casing wall can not mitigate casing failure caused by formation slippage, the casing in shale zone need a thin casing on the premise of other checks.

5.2 Optimization of casing steel grade

The above research and analysis results indicate critical casing shear displacement of casing shear-off is significantly less than casing collapse. So casing collapse condition can be ignored.

The casing of yield strength, tensile strength and elongation is influenced by the casing steel grade. According to the common belief, the more casing steel grade is, the harder the casing will damaged. However, the experimental data of Gao [Gao (2012)] show that the higher of alloy material yield strength is, the lower elongation will be. That means that the material from the initial plastic deformation to fracture deformation is smaller. High yield strength decreases the uniform deformation capacity of the material, and limits the material plastic deformation capacity which studied by Liang [Liang (1988)]. In the process of casing damage that caused by formation slippage, the bigger casing elongation has, the harder for the casing to break, and also more conducive to delay the casing damage. The new concept is very different form the common belief.

The maximum Von Mises stress of various steel casing grade with a wall thickness of 6.20 mm in the formation slippage progress is shown in Fig. 12.

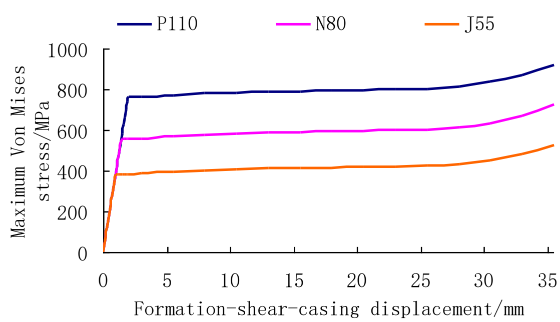


Figure 12: The maximum Von Mises of various casing steel

The maximum Mises stresses of the all steel grade casing are same before yield. With the increase amount of slip, J55, N80 and P110 casing yield in turn, and the maximum Mises stress growth rate slows down after yield. The tensile strength of three kinds of steel casing is different, and the critical shear casing slippage displacements are also difference between each other. Comparing the tensile strength of each steel grade, the critical shear casing slippage of J55, N80 and P110 casing are 34.99 mm, 33.74 mm and 32.49 mm separately. The calculation results show that, the low grade casing is more effective in delaying the shale zone casing shear.

Considering two factors including casing wall thickness and steel grade, low steel grade casing with a thin wall is selected to trip in the shale zone in order to delay casing failure.

Finite element calculations show the critical shear casing slip of high grade steel (P110) and thick casing (with a wall thickness of 10.54 mm) is 29.60 mm, and as a contract, the low grade steel (J55) and thin casing (with a wall thickness of 6.20 mm) has a critical shearing casing slip of 34.99 mm. The optimized casing makes the critical shear casing slip increases by 18.24%, and considering the space between the casing and well bore (d_w-D=60.3 mm), the critical casing failure slippage displacement increased from 89.9 mm to 95.3 mm, increased by 6.01%. Although the critical slippage difference is small, the low grade and thin casings have low costs, and they are easy to repair after failure. Therefore, the low grade thin casings can not only delaying casing damage induced by shale zone interface slippage, but also reducing the costs of oil field. This study can help oilfield avoiding that using high cost casing but no beneficial effect.

5.3 Prospect of the new properties of casing to delay casing failure

In the process of casing damage that caused by formation slippage, different steel grade casings have the large difference on stress, but the difference of maximum equivalent strain is small. The maximum equivalent strain of various grade casing with a wall thickness of 6.20 mm is shown in Fig. 13.

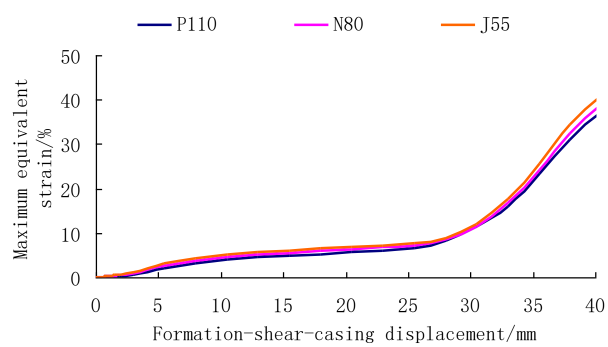


Figure 13: The maximum equivalent strain of various grade casing

Three kinds of casing steel grade have almost the same maximum equivalent strain in the shearing process. But they have the significantly different elongation, which means the critical strain of casing damage is obviously different. The maximum equivalent strain curve of casing is lightly influenced by strength and other parameters but greatly influenced by casing elongation. Therefore, more deformation before the casing failure is advantageous to delay the casing damage that caused by formation shear slippage.

In API standards of the casing, the maximum casing elongation is 30%, which makes the casing collapse critical value much lesser than that of casing shear-off. If the maximum casing material elongation is large enough, the casing shear-off critical value can become much larger, and even larger than the critical value of considering casing collapse. Assuming that a new casing material has the same parameters of J55 casing expect elongation, the critical casing impairment of the casing with a wall thickness of 6.20 mm is shown in Fig. 14.

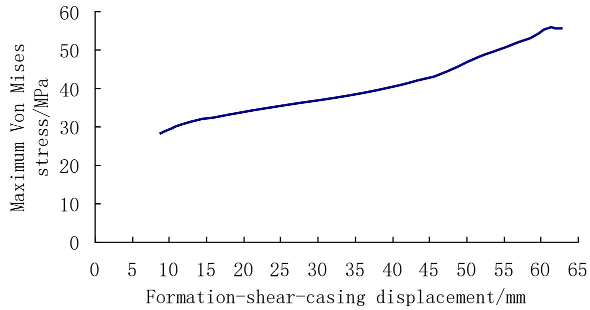


Figure 14: Elongation against critical casing impairment shearing displacement

It can known from the figure, the critical slip of casing damage will increase with the elongation increase, when the elongation increases to 61.16%, the critical casing failure slippage displacement will reach 115.69 mm and stop rising, which means that when the tube shucked in the well, the casing still able to maintain its integrity. So, high elongation casing can make the critical casing failure slippage displacement increase from 95.3 mm to 115.69 mm, increase 21.40%. Therefore, when the casing can reach the requirements under the premise on tension strength, internal pressure strength and outer pressure strength, it will effectively mitigate or delay casing failure in shale zone caused by formation slippage if the high elongation rate of new material casing is used.

6 Conclusions

(1) The stress on casing is much greater than that on the near-wellbore in the casing failure caused by formation slippage. The stress concentrated near the slippage interface. When the casing deformed greatly, then wellbore rock deformed less.

(2) Casing failure induced by formation slip is different from conventions. Casing cannot resist formation effectively. The casing deformed positively, and the casing elongation is the key parameter to avoid casing failure. Lower grade casing exhibits a larger critical slippage displacement because of its higher elongation capacity under stress.

(3) The critical formation slippage displacement can raise 20.23% larger than J55 casing with a wall thickness of 6.20 mm if a new marital casing with an elongation larger than 61.16% used in formations abundant with horizontal weak layers on the premise of checked.

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