Effect of Stratum on the Interfacial Stress and Structural Integrity of Cement Sheath

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Abstract. In order to determine the method of protecting the cement sheath structural integrity in oil and gas wells, the finite element mechanics models of the Casing-Cement sheath-Stratum Combination Body (CCSCB) were established based on different stratum action mechanism. The effect of stratum type, well depth, crustal stress and stratum elastic modulus on the interface stress and structural integrity of cement sheath were researched. The results show that, in the creep stratum, the interface contact pressure of cement sheath increase and the circumferential stresses reduce with the increase of crustal stress. There is no effect of the crustal stress on the interface stress in the elastic and rigid stratum. In elastic stratum and low crustal stress creep stratum, circumferential tensile stress would be generated at cement sheath when loading. The cement sheath is easy to crack by this tensile stress and the structural integrity is destroyed when the load was higher. The effect of stratum elastic modulus on the interface stress is related to the stratum and stress type. There is no influence of the elastic modulus on the interface stresses in the rigid stratum. The influence of the elastic modulus on the interface contact pressure is obvious in the elastic stratum, and the effect on the circumferential stress is obvious in the creep stratum.

Keywords: creep stratum; elastic stratum; rigid stratum; cement sheath; structural integrity.

1. Introduction
In recent years, some progress has been made in the mechanics analysis and research on the deformation and bearing capacity of cement sheath under the action of construction load, focusing on the problem of annular seal leakage in oil and gas wells or gas storage wells [1-15]. The mechanic model of the Casing-Cement sheath-Stratum Combination Body (CCSCB) were established. The influence on the crustal stress and the mechanic parameters of the cement sheath on the stress of the CCSCB were analyzed. The adaptability relationship between the cement sheath performance and its load were studied. The optimization method of mechanic parameters of cement sheath was put forward. The above research results have laid a foundation for the further study of the mechanic mechanism and safeguard of the structural integrity of cement sheath.

In the CCSCB, the mechanic response of the cement sheath under the load is closely related to the loading mode, load size, borehole geometry, casing properties, stratum properties, crustal stress and the mechanic properties of the cement sheath itself etc. Therefore, the key to the accurate analysis of the stress and deformation of the cement sheath is to establish the mechanic model of the CCSCB which is suitable for the mechanic characteristics of the stratum, based on the correct analysis of the interaction between the stratum and the cement sheath.

However, in the mechanic analysis and model building, most of the related achievements are set the stratum as creep stratum. It is considered that stress in the far field can always be loaded into the cement sheath. The mechanic properties that well rock can bear part or all crustal stress under steady
state of the wall of oil and gas wells are not taken into account. Therefore, based on the mechanics analysis of literature [3] and [4], three kinds of stratum with different material properties such as creep, elasticity and rigidity are selected to establish the mechanic model of the CCSCB. The influence of stratum environmental condition such as strata type, well depth, crustal stress, stratum elastic modulus on the interface stress and structural integrity of the cement sheath was analyzed, which can provide the basis for the reasonable design of methods and approaches for ensuring the reliability of the annular seal of cement sheath according to the stratum conditions or different well depths.

2. Mechanic Action between Stratum and Cement Sheath

Because oil and gas wells have different strata environments in project, the mechanic properties of strata of borehole wall will be different. Even strata at different depths in the same well could have different mechanic properties because of their different structures, compositions and microstructures. As a result, it shows different deformation characteristics and bearing capacity under the load, and then affects the mechanic interaction between the stratum and the cement sheath. The types of strata can be classified into creep stratum, elastic stratum and rigid stratum by the mechanics of materials and the theory of elastic-plastic mechanics.

2.1. Mechanic Action of Crustal Stress on Cement Sheath

**Creep stratum.** Creep rock is mainly composed of strata of rock salt, mudstone and shale. Under the action of far-field stress, creep deformation can occur. In cementing wells, the creep stress under long-term steady state can continue to act on the cement sheath and casing. That is, the stress in the far field can always be loaded on the cement sheath.

**Elastic stratum.** Under the action of external load, the rock stratum has the characteristics of elastic-plastic deformation. However, when the load size is within a certain range, the rock strata only produce elastic deformation or small amount of plastic deformation can be ignored and the elastic deformation is dominant. And its deformation is stable under long-term load. After unloading, it can completely (or basically) restore its original shape and size. At this time, the mechanic properties of strata can be idealized as elastic stratum. Under normal circumstances, these kinds of stratum such as tight sandstone and limestone can be roughly determined into the elastic stratum.

During well construction, the borehole wall formed by elastic stratum reaches the mechanic equilibrium under the effect of liquid column pressure and crustal stress to keep borehole wall stable. The stratum will not actively load crustal stress onto cement sheath when no load is applied in the casing after cementing. When construction load is applied in the casing, the stress and strain transfer of the casing and cement sheath, the surrounding rock of the well bore will have corresponding stress and strain changes. When the load in the casing is removed, the elastic deformation generated by the stratum will be restored to its original state. The stress between the borehole wall and the cement sheath occurs only at the initial stage of unloading. But there is no interaction between stratum and cement sheath when the borehole wall is restored to its original position.

**Rigid stratum.** Rigid stratum refers to the rock which only stress response is produced without any deformation under load. The mechanic properties of hard rock formation in deep depth can be generally idealized as a rigid stratum. In view of the mechanic characteristics of rigid strata, the crustal stress is borne by the borehole wall stratum. When the casing is added load or unloaded, the borehole wall stratum always generates no strain and does not exert any stress on the cement sheath.

2.2. The Finite Element Mechanic Model of Combination Body

According to the above analysis, the CCSCB are selected as figure 1 and the PLANE183 plane strain element is used to discrete the elements of the CCSCB of figure 1. The 1/2 model (Figure 2) is selected to analyze the stress and strain mechanics problems of the CCSCB under load such as loading and unloading in casing. The finite element mechanic model of the CCSCB is established for different kind of stratum. In the figure 1, the casing and borehole annulus are eccentric annulus. $p_h$, $p_b$ are respectively the original maximum, minimum horizontal crustal stress in the far-field.
The followings should be considered when the CCS CB was analyzed by mechanic analysis: (1) The borehole wall strata are selected as creep, elastic and rigid stratum respectively; (2) Non-uniform ground stress; (3) Eccentric casing; (4) The two load action form for the load and unload during casing pressure test construction are considered at the same time; (5) The bearing capacity of the cementation interface which formed by cement sheath and casing, cement sheath and stratum and the state of contact or dispersion of CCSCB are considered.

3. Results and Discussion

3.1. Effect of Crustal Stress on the Interfacial Stress of Cement Sheath in Different Stratum

Above analysis show that different stratum has different mechanic properties and bearing capacity, which affects the mechanic effect of crustal stress on the cement sheath. Figure 3 and figure 4 show the simulation results of the interface contact pressure and circumferential stress of cement sheath at narrow gap in eccentric annulus under the different crustal stress in different stratum.
In the figure 3 and figure 4, the stratum type, the cement sheath inner or outer interface, loading or unloading conditions are indicated by symbolic combination respectively. Where C, E and R respectively represent the creep, elastic and rigid stratum. L or U represent the loading or unloading state. I or O respectively represent the inner or outer surface of the cement sheath (the same below). In the simulation calculation, the selected basic condition parameters are as follows: Borehole diameter is 241.3 mm, casing diameter is 177.8 mm, casing thickness is 12.65 mm and casing eccentricity is 0.2. The fluid density in the borehole is 1200 kg/cm³. The depth of calculate point is 850 m. For casing the elasticity modulus is 210 GPa and the Poisson's ratio is 0.3. The surrounding rock stratum radius takes 1 m, and the stratum elastic modulus is 15 GPa, the Poisson's ratio is 0.2. For cement sheath, the elastic modulus is 7.86 GPa, the Poisson's ratio is 0.178, the yield strength is 20.3 MPa. The inner interface cementation strength is 0.6 MPa, and the outer interface cements strength is 0.18 MPa. The load added at well head is 30 MPa. During the process of calculating, the condations of five combination of the min and max crustal stress are selected as: 5,10 MPa, 7,10 MPa, 10,15 MPa, 10,18 MPa, 20,50 MPa. The calculation results in figure 3 and figure 4 show that: Under the conditions of non-uniform crustal stress and eccentric annulus, the interface contact pressure (positive value is compressive stress, negative value is tensile stress) at the wide gap of the cement sheath is higher than that at the narrow gap during the loading process in various kinds of strata. However, the circumferential stress (positive is tensile stress and negative is compressive stress) of the inner interface at the narrow gap of the cement sheath is always higher than that at the wide gap, which is the weak point of brittle tensile failure of the cement sheath.
The effect of the crustal stress on the cement sheath is only limited to the creep stratum, and there is no influence of crustal stress in the elastic and rigid stratum. For creep stratum, the overall influence trend of crustal stress on the interface stress of cement sheath is as follows: the crustal stress increases (minimum or maximum crustal stress increases), the contact pressure on the inner and outer surfaces of cement sheath increases, and the circumferential stress decreases.

High circumferential tensile stress appears in cement sheath under the conditions of partial strata and crustal stress according to figure 3. When the tensile stress exceeds the tensile strength of the cement sheath, local or integral tensile cracks will appear in the cement sheath and the structural integrity is damaged. This situation mainly occurs in elastic stratum and low-stress creep stratum. For example, when the crustal stress in elastic stratum are 5,10MPa and the cement sheath tensile strength is 4.0MPa, the whole body of cement sheath produces tensile cracks at the wide and narrow gaps. Therefore, full attention should be paid to the high circumferential tensile stress of the cement sheath at the narrow gap in the elastic stratum under the conditions of eccentric annulus when evaluating the structural integrity of the cement sheath and designing the mechanic parameters of the cement sheath.

3.2. Effect of Stratum Types on the Interfacial Stress of Cement Sheath

Figure 5 and figure 6 show the curves of the interface contact pressure and circumferential stress of the cement sheath during the loading and unloading under different stratum and well depth. In order to compare and analyze the influence of stratum type on the interface stress of cement sheath, the borehole wall stratum is assumed to be creep, elastic and rigid stratum respectively, and the variation of stratum type with depth is not considered.

The basic condition parameters selected in the calculation are as follows: casing eccentricity is 0. Elastic modulus is 15GPa and Poisson's ratio is 0.25 of the well surrounding rock. For cement sheath, elastic modulus is 4.75GPa, yield strength is 14.8MPa, Poisson's ratio is 0.178 and tensile strength is 3.1MPa. The remaining conditions are consistent with the corresponding parameters of the figure 3.

According to the engineering practice, the variation of hydrostatic pressure of working fluid and crustal stress with the depth of well is considered. Figure 5a shows that when there is a fluid with a specific density in the casing, the interface contact pressure values of the cement sheath are the same for the creep and elastic stratum at the surface wellhead, which both are lower than that of the rigid stratum. With the increase of well depth, the casing load and crustal stress increases, and the inner interface contact pressure of cement sheath increase under different geological conditions. But the increase degree is different, the stress increased obviously in the creep stratum. This is mainly due to that the cement sheath interface contact pressure is only depended on the casing load in the elastic and rigid stratum, but the contact pressure is generated both by the casing load and crustal stress CCSCB in the creep stratum.

At the beginning of well depth increase, the interface stress of cement sheath of creep stratum is lower than that of rigid stratum. When the depth of a well reaches a given deep, with the depth increase continually, the effect of crustal stress increase, and the interface stress of cement sheath of creep stratum is higher than that of rigid stratum. When the well depth reaches 3000m, the inner interface of the cement sheath in the creep and rigid stratum are all yield. Within the well depth given in this paper, the interface contact pressure of the cement sheath in the elastic stratum is the lowest.

When load at the wellhead is withdrawn after operation and the hydrostatic pressure and crustal stress are still maintained in well, interface contact pressure of cement sheath with elastic deformation in the loading process is restored to the original loading state in the well. During the process of loading, the cement sheath occurs yield local or overall. Cement sheath deformation cannot fully recover after unload. The interface contact pressure will reduce. At this point, if the crustal stress is low (or no pressure) and in the situation of no crustal stress action in elastic strata, rigid stratum, the interface contact stress of cement sheath will turn to be tensile stress from compressive stress. There is a potential risk of tearing apart the bond interface of the cement sheath.

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The circumferential interface stress of the cement sheath varies with the well depth and stratum types during loading and unloading (Figure 6a). In case of loading, circumferential tensile stress is generated in both the inner and outer surfaces of the cement sheath under the condition of creep formation and elastic formation at the wellhead, and the values are the same. While in the case of rigid stratum, the inner interface circumferential stress is tensile stress, and the outer is compressive stress. Under the confining pressure and crustal stress in the creep formation, the inner and outer interface circumferential stress of the cement sheath decreases with the increase of well depth and the stress state gradually changes from tensile to compression deformation. The crustal stress cannot be acted on cement sheath in the elastic stratum due to the borehole wall can bear the crustal stress. Under the action of internal pressure in casing, the inner and outer interface circumferential stresses of cement sheath are tensile stress. The deeper the well depth, the higher the tensile stress is. For a certain well depth, the tensile crack could be made at the interface or in the internal part of cement sheath when the inner interface tensile stress is higher than the tensile strength, so the structure integrity of cement sheath is destroyed. Under the condition of rigid stratum, the interface circumferential stress of cement sheath increases first and then decreases with the increase of well depth, while the outer circumferential stress of cement sheath always shows a downward trend.
Figure 5b and figure 6b are obtained with hydrostatic pressure or crustal stress remaining in the well after the wellhead load is removed. When only elastic deformation occurs to the cement sheath in loading process, the interface circumferential stress of the cement sheath reverts to the loading state of hydrostatic-liquid column pressure or crustal stress in the well after unload in various kinds of stratum. The above analysis results show that, during the process of loading or unloading in the oil and gas well construction, the well depth will have an impact on the interface stress and structural integrity of the cement sheath, and the degree and law of the impact is closely related to the stratum type. In fact, with the change of well depth, the composition and mechanic properties of surrounding rocks in wells will change, and even the material mechanic constitutive relationship will also change, which made the stratum to belong to creep, elasticity, rigidity respectively. Therefore, the effect of well depth on stratum type and rock properties must be considered in the mechanic analysis and structural integrity evaluation of cement sheath in the wells.

3.3. Effect of the Stratum Elastic Modulus on the Interfacial Stress of the Cement Sheath

Using the calculation situation parameters of figure 3 and figure 4, make minimum and maximum horizontal crustal stress in inhomogeneous stress stratum for 10MPa and 15MPa, figure 7 and figure 8 show the influence of elastic modulus on the interface contact pressure and circumferential stress at narrow gap of cement sheath in different stratum after load and unload, which the elastic modulus are selected as 5,7,10 and 20GPa respectively.

![Figure 7](image1.png)
![Figure 8](image2.png)

**Figure 7.** Effect of formation type and elasticity modulus on interface contact pressure

**Figure 8.** Effect of formation type and elasticity modulus on interface contact pressure

The results show that, there is no influence of elastic modulus on the stress of cement sheath in the rigid stratum. The elastic modulus of the elastic stratum has an obvious influence on the interface contact pressure of the cement sheath while the elastic modulus of the creep stratum has a more obvious influence on the interface circumferential stress. For creep stratum, with the increase of elastic modulus, the inner interface contact pressure of cement sheath increase and the outer’s decrease, the interface circumferential stress are both increase. For elastic stratum, the interface contact pressure increase and the circumferential stress decrease with the increase of elastic modulus.

The key basic condition is that the stratum type determines the interaction mode between crustal stress and cement sheath, and restricts the effect of parameters such as the stratum elastic modulus on the interface stress and structural integrity of the cement sheath. Therefore, when carrying out mechanic analysis of cement sheath, structural integrity evaluation and mechanic parameter design of cement sheath, it is necessary to accurately evaluate and determine the stratum type of specific depth stratum based on accurately determining the crustal stress and stratum rock mechanic properties.
4. Conclusion

- In creep stratum, with increase of crustal stress, the contact pressure of cement sheath increase, but circumferential stress decrease; In elastic stratum and rigid stratum, there is no influence of crustal stress on interfacial stress of cement sheath.
- In elastic stratum and creep stratum with low crustal stress, when the load or cement sheath elastic modulus is high, the cement sheath is cracked easily due to high circumferential tensile stress so that broke the integrity of cement sheath structure. Under the condition of inhomogeneous crustal stress and eccentric annulus, annular narrow gap is the weakest part of the cement sheath.
- With the increase of well depth, the inner and outer interface contact stress of the cement sheath increase obviously in the creep stratum, and the inner and outer interface circumferential tensile stress of the cement sheath increase in elastic stratum. There will be a potential risk that the inner interface of cement sheath is cracked and structure integrity is broken in elastic stratum.
- There is no influence of elastic modulus on the stress of cement sheath in the rigid stratum. The elastic modulus of the elastic stratum has an obvious influence on the interface contact pressure of the cement sheath while the elastic modulus of the creeping stratum has a more obvious influence on the interface circumferential stress.

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