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Effect of interface defects on shear strength and fluid channeling at cement–interlayer interface

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ABSTRACT

The fluid channeling during hydraulic fracturing has been seriously restricting the efficient development of low permeability oilfield and CBM Field. The occurrence of fluid channeling after hydraulic fracturing is hinged on shear strength at cement–interlayer interface (CII) and hydraulic fracturing pressure. Interface defects are key factors that influence the shear strength at CII. In view of this, the influence of interface defects on shear strength at CII and fluid channeling is discussed in this paper.

The formation reasons of interface defects are analyzed firstly. Based on analysis of the essence of shear strength at CII, it is concluded that all interface defects amount to the missing amount of mud cake ring. Then a mathematical model between missing amount of mud cake ring and shear strength at CII is developed. In order to verify the accuracy of the model, a simulated experimental system is built. Based on the model and fluid channeling coefficient equation, a modified version of the fluid channeling coefficient is derived and the influence of interface defects on interlayer fluid channeling during hydraulic fracturing is evaluated quantitatively.

The results revealed that the shear strength at CII decreases linearly with the increase of interface defects, and verification results show that the relative errors between calculated values by the model and experimental values are less than 10%. From the modified equation of the fluid channeling coefficient, this paper established a typical exponential relationship between missing amount of mud cake ring and fluid channeling coefficient, which indicates that interface defects drastically affect fluid channeling at CII.

1. Introduction

Hydraulic fracturing is still an effective technology for the development of petroleum and coal-bed methane (CBM) reservoirs with low-permeability (Bohloli and de Pater, 2006; Gu and Chen, 2010; Magnus, 2011; Rahman and Joarder, 2006). But after the hydraulic fracturing operation, the high water cut or sudden water flooding of oil well usually occurs due to the upward migration of bottom water, which is called fluid channeling. This problem has been severely limiting the effect of hydraulic fracturing (Ma et al., 2008; Qiao et al., 2008; Zhao et al., 2009).

Some studies show that the interlayer and cement paste themselves will not be crushed under hydraulic fracturing pressure (Devloo et al., 2006; Sun et al., 2003; Yoshihara, 2008), and the fluid channeling occurs at cement–interlayer interface (CII; Liu et al., 2008; Wang, 2006). Only when the shear strength that acted on CII during hydraulic fracturing is greater than the shear strength at CII itself, will the CII be destroyed and channels for fluid channeling at CII form (Ladva et al., 2005). Subsequently, the bottom water will migrate into the reservoir, and fluid channeling occurs (Sun et al., 2003). So the shear strength at CII is a key factor to the fluid channeling at CII. The study shows that interface defects will reduce the shear strength at CII (Gu et al., 2008; Zhao et al., 1996). However, this issue is rarely studied.

The work presented here proposes the relation model between interface defects and shear strength at CII by equivalently converting the interface defects. In order to verify the accuracy of this model, a simulated experimental system is built independently.

2. The model

2.1. Formation reasons and equivalent convertion of interface defects at CII

The formation reasons of interface defects at CII are analyzed as follows:

(1) Under formation temperature, the mud cake between cement sheath and borehole wall will become pulverized due to dehydration and peeling off, which causes micro-cracks.

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(2) The evaporation of absorptive water and capillary water from the calcium silicate hydrate (C-S-H) in the cement sheath can lead to the concaving of free surface and increase in surface tension. Because the tension on water meniscus needs to be balanced by the surrounding compressive stress, the compressive stress on the cement sheath will increase. It will, in turn, lead to volume reduction and dry shrinkage of the cement sheath, and hence the micro-cracks at CII emerge.
(3) The cement sheath itself may shrink, swell, or suffer external force. All of these will result in the deformation of cement sheath, which can cause the cement sheath to crack and peel off from the borehole wall. In this case, the mud cake loses support and then cracks under gravity.
(4) The values of creep and strain will increase due to the migration of water and increase of stress gradients, which will cause remarkable stress release. Eventually, it can lead to the formation of micro-cracks at CII.
(5) The oil and water in formation can permeate into the mud cake through the weak CII, which tends to dissolve. It can cause cementation failure between cement sheath and interlayer, which will result in larger micro-cracks at CII.

Because the mud cake is the weak link at CII, the shear strength at CII is actually reflected by the shear strength of mud cake. Essentially, the mud cake can be treated as soil. According to the knowledge of soil mechanics, the shear strength of soil mainly depends on the friction between clay particles. From the macroscopic view, the shear strength at CII mainly depends on the friction force at the sliding failure surface inside of mud cake ring. Based on this, all the interface defects can amount to the missing amount of mud cake ring at CII.

2.2. Definition of shear strength at CII

The shear strength at CII is the shear force on unit area of interface between cement sheath and interlayer. It can be expressed by

$$p = \frac{F}{S_c} = \frac{10F_s}{\pi h D} \tag{1}$$

where p is shear strength at CII (MPa), F is force (kN), S_c is area of cylindrical surface (cm^2), F_s is shear force at CII (kN), which mainly depends on the friction force of mud cake at CII, and can be measured in laboratory, h is interlayer thickness (cm), and D is borehole diameter (cm).

Eq. (1) is just the definition for p. It cannot reflect the effect of missing amount of mud cake ring on p.

2.3. Theoretical derivation of mathematical model

In addition to the assumption that all the interface defects are equivalent to the missing amount of mud cake ring at CII, other assumptions are listed as follows:

(1) Because the mud cake is a weak link in the isolation system of CII, the sliding failure surface is supposed to take place inside of the mud cake ring, when the CII is destroyed under shear force.
(2) The F_s is assumed equal to the sliding friction force on sliding failure surface.
(3) The thickness of mud cake ranges from 0.5 to 2 mm usually, while the borehole diameter usually ranges from 152.4 to 215.9 mm in China. Thus the thickness of mud cake is so far less than the borehole diameter that the formation pressure and borehole pressure can be considered to act on the sliding failure surface directly.
(4) The missing amount of mud cake ring is considered to be continuous and uniform.
The cross section diagram of well completion and stress analysis of mud cake ring at CII are shown in Fig. 1.

As shown in Fig. 1a, there are four rings from inside to outside, which represent casing, cement sheath, mud cake and interlayer. Among them, the mud cake ring has a missing amount that characterizes the equivalent interface defects at CII.

In Fig. 1b, p_f is horizontal formation pressure (MPa), and p_b is borehole pressure (MPa), and they both distribute uniformly on the mud cake ring horizontally. F_s is the shear force that acted on mud cake (kN). f_s is sliding friction force (kN). It is supposed that F_s and f_s are a pair of balance forces when the mud cake slides along the failure surface, and are equal in value but contrary in stress direction. L is the missing amount of mud cake ring (cm), and a value 0 to L means that the mud cake ring is complete.

Eq. (2) shows the sliding friction when the mud cake ring slides under shear force:

$$f_s = \mu N \tag{2}$$

where μ is coefficient of sliding friction, and N is normal force.

According to the stress analysis of mud cake ring in Fig. 1b, N is resolved from the radial resultant force of formation pressure and borehole pressure, which has an axial effect on f_s. So N can be expressed by

$$N = |p_f - p_b| S_{mc} = |p_f - p_b| (\pi D - L) h \tag{3}$$

where S_{mc} is cylindrical area of mud cake ring (cm^2).

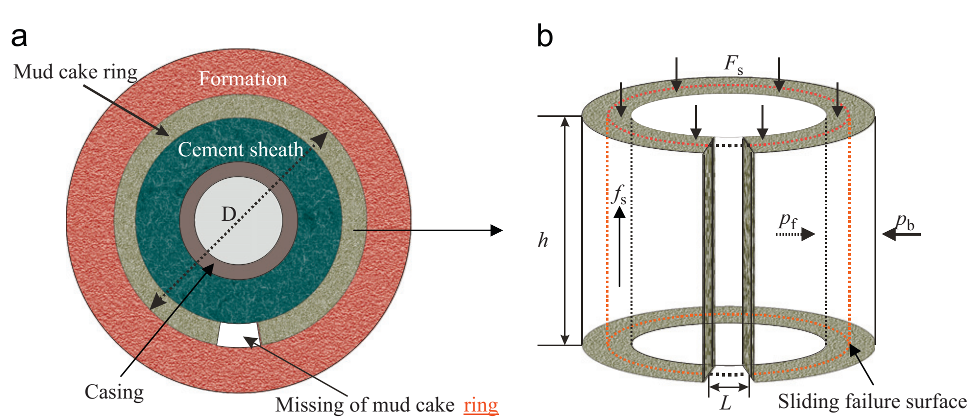

Fig. 1. The stress analysis of mud cake ring at CII. (a) Cross section diagram of well completion. (b) Stress analysis of mud cake ring.