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Mechanical analysis and design of casing in directional well under in-situ stresses

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ABSTRACT

Casing deformation and collapse hamper the regular drilling, production and downhole operation. The casing in directional well under the action of inelastic surrounding rock displays a complex mechanical state. Taking the in-situ stresses and well trajectory into account, the mechanical model of casing in directional well under in-situ stresses is established. By coordinate rotation, the three principal in-situ stresses are converted to a stress tensor in the wellbore coordinate. The mechanical interaction of casing and surrounding rock is simplified to a generalized plane strain problem. Based on the theory of pressurized hole in plate, the stress of the infinite surrounding rock is calculated. To analyze the casing behavior, the complicated solution is divided into three simpler problems: the elastic mechanics analyses under mean stress, deviator stress and shear stress respectively. The analytical expressions of casing stress and load in directional well under in-situ stresses and inside hydrostatic pressure are deduced. This analytical solution is verified by numerical simulation. Furthermore, casing design for the directional well through complex formation in an oilfield has been conducted. The results can remedy the current standards of casing design and guide the well integrity design in directional well under in-situ stresses.

1. Introduction

With the development of petroleum exploration and drilling technology, more directional wells have been drilled in complex geological environment. Although the casing design standards, such as API, ГОСТ and SY/T, have been amended for many times (API, 1994; NDRC, 2008), there are still a lot of casings designed obeying the standards failure. The current standards only consider hydrostatic pressure and gravity of overburden formation in the anhydrite and salt interval simply. It has been proved that casings bear not only the above loads but also the formation forces (Huaiwen and Xueshi, 1991). In the inelastic formations, such as salt rock and shale rock, casings will gradually bear the mechanical action of surrounding rock (Willson et al., 2002; Poiate et al., 2006). After a long time, the mechanical action will tend to a steady pressure, which is named in-situ stresses' load (Li and Yin, 2006). The processes of casing collapse are different when the external load is applied by solid formation or fluid (Morita et al., 2005). So, it is significant to analyze and design the casings in directional wells under in-situ stresses.

According to the elastic theory, the mechanical behavior of casings in vertical wells under the in-situ stresses can be analyzed by simplifying to a plane strain problem (EI-Sayed and Khalaf, 1992; Yin and Gao, 2012; Li et al., 2012). The finite element analysis (FEA) is also used to simulate the stresses of casing, cement, and formation (Chatterjee and Mukhopadhyay, 2003; Nabipour et al., 2010). The difference between the theoretical calculation and the FEA solution for von Mises stress is tiny (Rodriguez et al., 2003). In view of application, casing deformation caused by tectonic forces in Andean Foothills has been evaluated and managed (Last et al., 2006). But, the research on the mechanical behavior of casings in directional wells under the in-situ stresses is rare. A plane model for the stress field around an inclined, cased and cemented wellbore was developed by Atkinson and Eftaxiopoulos (1996). The stress distribution around an inclined cased wellbore can be simulated by numerical model (Li et al., 2005; Jo and Gary, 2010).

The axis of a directional well is not perpendicular to the plane of the horizontal in-situ stresses any more. The casing and surrounding rock will display the mechanical interaction in a three-dimensional space. The mechanical analysis for this problem is very difficult to obtain and the design standard is lacked. To address the issue, comprehensive application of the coordinate rotation, the theory of pressurized hole in plate, the theory of composite cylinder

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and the method of stress function, the analytical expressions of casing stress and load in directional wells under in-situ stresses are deduced. Furthermore, the numerical simulation is performed to verify this analytical solution. The research results have been applied for casing design in one oilfield successfully.

2. The in-situ stresses in wellbore coordinate

The stress field of deep formation is usually described by triaxial principal in-situ stresses, which include the horizontal maximum in-situ stress, the horizontal minimum in-situ stress and the vertical in-situ stress (σ_H, σ_h and σ_v). The magnitude and orientation of in-situ stresses can be determined by borehole breakout and acoustic emission Kaiser etc. The stress field in vertical wells is consistent with in-situ stresses. But the situation of casings in directional wells is different. The schematic diagram of the casing in directional well under in-situ stresses is shown in Fig. 1.

The coordinate system of the principal in-situ stresses (x_0, y_0, z_0) is established, and the directions of coordinate axis are consistent with in-situ stresses σ_H, σ_h and σ_v respectively. In order to be convenient to analyze the casing behavior, the in-situ stresses are converted to the stress tensor in the wellbore coordinate system by adopting coordinate rotation matrix. The Oz axis of wellbore coordinate (x, y, z) is established along with the axis of the wellbore. The Ox axis and Oy axis lie in the plane that is vertical with the axis of the wellbore.

Arbitrary rectangular coordinate system can be obtained by three-time rotations from the original coordinate system. The rotate angle are called Euler angle. According to right-hand rule, the direction cosine matrixes rotating around x-axis, y-axis and z-axis (Zhu et al., 2010) are:

$$\mathbf{C}_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_x & \sin\alpha_x \\ 0 & -\sin\alpha_x & \cos\alpha_x \end{bmatrix} \tag{1}$$

$$\mathbf{C}_y = \begin{bmatrix} \cos\alpha_y & 0 & -\sin\alpha_y \\ 0 & 1 & 0 \\ \sin\alpha_y & 0 & \cos\alpha_y \end{bmatrix} \tag{2}$$

$$\mathbf{C}_z = \begin{bmatrix} \cos\alpha_z & \sin\alpha_z & 0 \\ -\sin\alpha_z & \cos\alpha_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

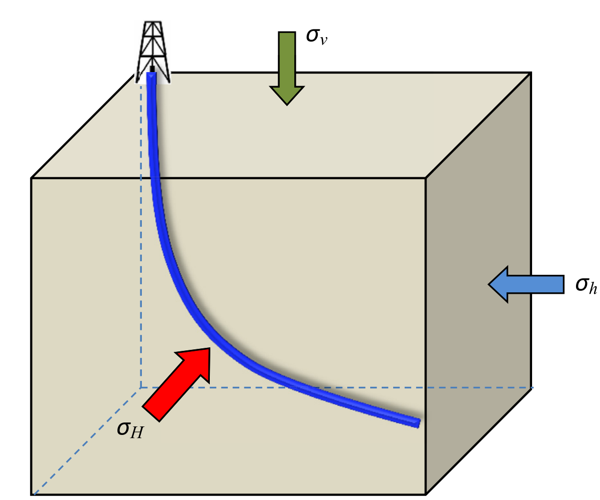

Fig. 1. Schematic diagram of casing in directional well under in-situ stresses.

The coordinate rotation matrix is formed by multiplying direction cosine matrix in reversed order. Now, we will build the coordinate rotation matrix from the coordinate system of principal in-situ stresses to wellbore coordinate system. The wellbore deviation angle is α, and the angle between wellbore azimuth and horizontal maximum in-situ stress is β. The coordinate rotation process is: firstly rotating β around z_0-axis, then rotating α around y_1-axis (the y_0 after the first time rotation). The coordinate rotation process from the coordinate system of principal in-situ stresses to wellbore coordinate system is shown in Fig. 2.

The coordinate rotation matrix can be expressed as:

$$\mathbf{C} = \mathbf{C}_y\mathbf{C}_z = \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta & -\sin\alpha \\ -\sin\beta & \cos\beta & 0 \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta & \cos\alpha \end{bmatrix} \tag{4}$$

So, the three principal in-situ stresses are converted to the stress tensor in the wellbore coordinate (Hossain et al., 1999; Garrouch and Ebrahim, 2001; Liu et al., 2005). The stress tensor in the wellbore coordinate is:

$$\begin{bmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{bmatrix} = \mathbf{C} \begin{bmatrix} \sigma_H & & \\ & \sigma_h & \\ & & \sigma_v \end{bmatrix} \mathbf{C}^T \tag{5}$$

The formation stress acting on casing in directional well can be obtained by substituting principal in-situ stresses, wellbore deviation angle and wellbore azimuth to the Eq. (4) and Eq. (5). The stress field of surrounding rock in wellbore Cartesian coordinate system can be rewritten as follow:

$$\begin{cases} \sigma_{xx} = \sigma_H\cos^2\alpha\cos^2\beta + \sigma_h\cos^2\alpha\sin^2\beta + \sigma_v\sin^2 a \\ \sigma_{yy} = \sigma_H\sin^2\beta + \sigma_h\cos^2\beta \\ \sigma_{zz} = \sigma_H\sin^2\alpha\cos^2\beta + \sigma_h\sin^2\alpha\sin^2\beta + \sigma_v\cos^2 a \\ \tau_{xy} = -\sigma_H\cos\alpha\cos\beta\sin\beta + \sigma_h\cos\alpha\cos\beta\sin\beta \\ \tau_{xz} = \sigma_H\sin\alpha\cos\alpha\cos^2\beta + \sigma_h\sin\alpha\cos\alpha\sin^2\beta - \sigma_v\sin\alpha\cos\alpha \\ \tau_{yz} = -\sigma_H\sin\alpha\cos\beta\sin\beta + \sigma_h\sin\alpha\cos\beta\sin\beta \end{cases} \tag{6}$$

3. Mechanical analysis of casing in directional well

To simplify the analysis process, the cement sheath is neglected because its material is similar with formation. The axial length is far

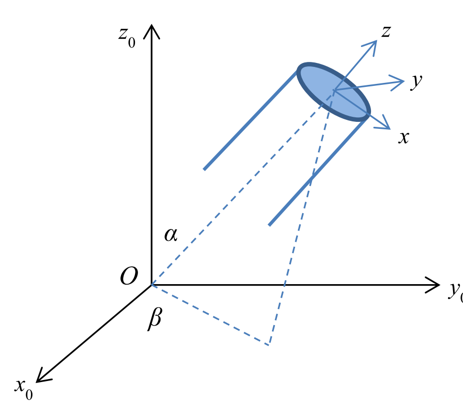

Fig. 2. The coordinate rotation process.