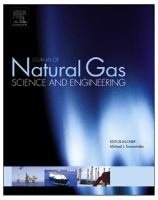
Journal of Natural Gas Science and Engineering 26 (2015) 409–418

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse



On the collapse resistance of multilayer cemented casing in directional well under anisotropic formation

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ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form
27 May 2015
Accepted 28 May 2015
Available online 26 June 2015

Keywords:
Multilayer cemented casing
Collapse resistance
Directional well
Anisotropic formation

ABSTRACT

In this paper, the mechanical characteristics of a multilayer cemented casing system in directional well under anisotropic formation have been presented to investigate the collapse resistance of casing under non-uniform in-situ stress. The model has considered the deviation angle, azimuth angle and the formation transverse anisotropy simultaneously. During analysis, the original in-situ stress tensor has been transformed into three stress tensors through the conversion of coordinate and stress decomposition based on the elastic mechanics. The formation mechanical parameters (Young's modulus and Poisson's ratio) have been taken as a function of wellbore circumferential angle during analysis procedure. In addition, a simplified model has been analyzed to verify the correctness of the method proposed in this paper. Subsequently, the stress distributions of the system have been obtained through solving the governing equations. On this basis, the influences of geometric parameters and mechanical parameters on the casing collapse resistance have been discussed to acquire a comprehensive understanding of this problem. Finally, some significant conclusions have been drawn based on the discussion mentioned above.

1. Introduction

With the continuous development of drilling technology, more and more directional wells are being drilled in complex geological condition, which means that multilayer cemented casing are required to seal the stratum and strengthen the wellbore. However, the wellbore integrity issues usually come into being duo to the non-uniform load imposed on the casing. (Pattillo et al., 1995; Garrouch et al., 2001; Simangunsong et al., 2006). Furthermore, in the standards recommended by American Petroleum Institute (API), the evaluative criterions of casing design are based on uniform load, and corresponding failure data of casing under non-uniform load is insufficient (API BULL 5C3, 1994). So, in this sense, it is particularly necessary and important to assess the casing capacity of collapse resistance under non-uniform in-situ stress.

Scholars have done quite a number of studies on this topic in the past few decades. According to the load properties, the mechanical model can be simplified as a plane strain problem, and the model can be solved through the theoretical method (Jo and Gray, 2010; Mueller et al., 2004; E1-Sayed et al., 1967; Fang et al., 1995; Wang et al., 2014a, 2014b), as well conducted in the framework of finite element software (Hoeink et al., 2012; Nabipour et al., 2010; Rodriguez et al., 2003; Fang et al., 1997, 1999). Moreover, some scholars have done relevant lab experiments on collapse resistance of cemented casing to verify or revise the theoretical derivation (Evans et al., 1972; Deng et al., 2005; Fuh et al., 2009). In addition, Pattillo et al. (1995, 2004) have provided both theoretical and experimental evidence on the mechanical characteristics of a concentric casing system in non-uniform load environment. EI-Sayed et al. (1991, 1992) have discussed two cases of opposing unidirectional collapse loads uniformly distributed along the diameter of a single casing string and two cemented concentric casing strings. Besides, a series experiments have been conducted by Morita et al. (2005) to investigate the distinctions of casing string under fluid force and geotectonic loads.

The studies mentioned above have laid a solid foundation for this issue. However, the wellbore deviation angle and azimuth angle as well the formation transverse anisotropy are neglected in the current researches. Actually, directional sections and formation transverse anisotropy are objective existence in drilled wellbore (Gao et al., 1994) due to the impact of geological structure, fault and crustal movement (Li et al., 2005; Gao et al., 1997; Zhang et al.,

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http://dx.doi.org/10.1016/j.jngse.2015.05.030
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2003). The literature describing the casing collapse resistance with simultaneously considering the deviation angle, azimuth angle and the formation transverse anisotropy have not been reported. As a consequence of this, the mechanical model and corresponding calculation method have been established to characterize the multilayer cemented casing strings with taking all the above influence factors into consideration in this paper. The method proposed herein is obviously appropriate for engineering problems which can be modeled as a multilayer ring-like combination system. Therefore, the research has guiding significance to casing design and collapse resistance assessment in complex formations.

The remainder of the paper is organized as follows. The coordinate transformation and stress decomposition are presented in Section 2. Section 3 is the main body of this paper, where the mechanical model and calculation method are described. In Section 4, the major source and relevant calculation method of formation transverse anisotropy have been stated. The model validation, case study, parameter sensitivity analysis and corresponding discussions are given in Section 5 and the major conclusions of this study are drawn in Section 6.

2. Coordinate transformation and stress decomposition

2.1. Coordinate transformation

As shown in Fig. 1, casing in directional wellbore are subjected to the triaxial principal in-situ stress, namely the vertical principal stress σ_v, the maximum horizontal principal stress σ_H and the minimum horizontal principal stress σ_h. The vertical principal stress is mainly induced by the overburden pressure. Whereas, the two kinds horizontal principal stress consist of two portions: one is induced by the overburden pressure, which is a function of formation Poisson's ratio; the other is resulted from the geological tectonic stress, which is different along the two horizontal directions. The most common techniques for in-situ stress determination include: acoustic velocity method, borehole breakouts method, well deviation statistics method, acoustic emission method and hydraulic cracking method (Chen et al., 2008).

The details of coordinate systems (X, Y, Z), (x_1, y_1, z_1), (x, y, z) and (r, θ, z) are presented in Fig. 2. As shown in Fig. 2, the directions of the original coordinate system (X, Y, Z) are opposite with σ_H, σ_h and σ_v respectively, oz axis coincides exactly with the well axial direction, while ox and oy is perpendicular to the borehole axial. In order to establish the relationship between(x,y,z) and (X, Y, Z), the coordinate transformation of (X, Y, Z) is conducted by the following manner (Chen et al., 2008; Guo, 2011):

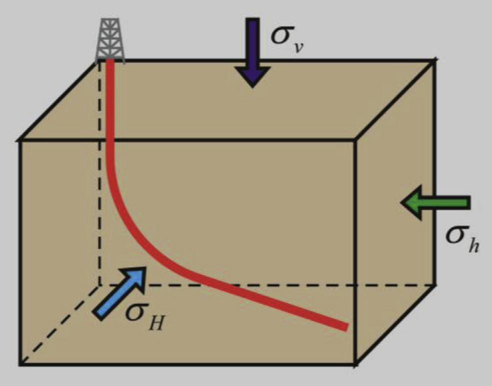

Fig. 1. Schematic diagram of directional well under in-situ stresses.

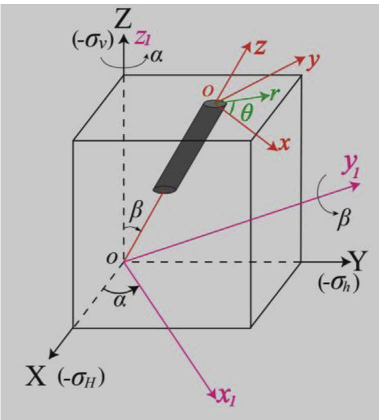

Fig. 2. Coordinate transformation of in-situ stress tensor.

(1) First, taken OZ as the axle of revolution, rotate the coordinate system$(X, Y, Z)\alpha$ degrees according to the right-hand rule to transform into (x_1, y_1, z_1), where α is the wellbore azimuth angle and the transformation tensor of this step is $\mathbf{C_Z}$.
(2) Second, taken oy_1 as the axle of revolution, rotate the coordinate system $(x_1, y_1, z_1)\beta$ degrees according to the right-hand rule to transform into (x, y, z), where β is the wellbore deviation angle and the transformation tensor of this step is $\mathbf{C_{y1}}$.

Therefore, the relationship between (x, y, z) and (X, Y, Z) can be represented by:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \mathbf{C_{y1}C_Z}\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{1}$$

If supposing $\mathbf{C} = \mathbf{C_{y1}C_Z}$, the stress tensor $\boldsymbol{\sigma}$ describing the stress field in the coordinate system (x,y,z) can be written as (Chen et al., 2008):

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} = \mathbf{C}\boldsymbol{\sigma}_0\mathbf{C}^T \tag{2}$$

where, $\mathbf{C_{y1}} = \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix}$; $\mathbf{C_Z} = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$

and$\boldsymbol{\sigma_0} = \begin{bmatrix} \sigma_H & & \\ & \sigma_h & \\ & & \sigma_V \end{bmatrix}$.

Eq. (2) can also be written as the following form:

$$\begin{cases} \sigma_{xx} = \sigma_H\cos^2\beta\cos^2\alpha + \sigma_h\cos^2\beta\sin^2\alpha + \sigma_v\sin^2\beta \\ \sigma_{yy} = \sigma_H\sin^2\alpha + \sigma_h\cos^2\alpha \\ \sigma_{zz} = \sigma_H\sin^2\beta\cos^2\alpha + \sigma_h\sin^2\beta\sin^2\alpha + \sigma_v\cos^2\beta \\ \sigma_{xy} = -\sigma_H\cos\beta\cos\alpha\sin\alpha + \sigma_h\cos\beta\sin\alpha\cos\alpha \\ \sigma_{xz} = \sigma_H\cos\beta\sin\beta\cos^2\alpha + \sigma_h\cos\beta\sin\beta\sin^2\alpha - \sigma_v\cos\beta\sin\beta \\ \sigma_{yz} = -\sigma_H\sin\beta\cos\alpha\sin\alpha + \sigma_h\sin\beta\cos\alpha\sin\alpha \end{cases} \tag{3}$$

2.2. Stress decomposition

Once the well completion is accomplished, the casing longitudinal deformation is restricted completely. Then, the stress