Journal of Petroleum Science and Engineering 107 (2013) 45–49

Contents lists available at SciVerse ScienceDirect

Journal of Petroleum Science and Engineering

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

Cement failure probability analysis in water injection well

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ARTICLE INFO

Article history:
Received 1 November 2011
Accepted 26 April 2013
Available online 14 May 2013

Keywords:
cement failure
injection wells
probability analysis
random variables

ABSTRACT

In the petroleum industry, the salt water was produced along with oil and gas. Due to the environment issue, the oil companies choose, the cheap and convenient way, to inject salt water into the reservoir. Because of the cycle load that injects water periodically, the cement fatigue failure should be considered in cement design. In this paper, the cement compressive failure, shear failure, tensile failure and fatigue failure modes were considered with different bottomhole pressures. The uncertainties of casing mechanical properties, cement mechanical properties, formation mechanical properties and wellbore geometry were also considered in the study. Based on the analysis, it is shown that within the cement compressive strength requirement, the wellbore service life can be increased by enhancing cement plastic behavior. The elastic cement with higher plasticity showed better behavior than brittle cement though the brittle cement has higher compressive strength.

1. Introduction

The main objective of cementing operation is to provide zonal isolation of the formations which have been penetrated by the wellbore and provide support to the casing. Even if the initial cement was properly placed and initially provides a competent hydraulic seal, formation stresses and large changes in wellbore pressure and temperature from a variety of common well events could easily crack a cement sheath during service of the well. In water injection wells, water was injected into the reservoir formation through the well periodically. There were injection pressure load cycles during the service of the well. The load cycles can cause cement failure if the cement was not designed properly.

The theory of thermo-poro-elasticity was used to predict the various modes of cement failure. The cement is assumed to behave as an elastic-brittle material (Thiercelin et al., 1998). A stress-modeling and risk analysis methodology was proposed using a complementary suite of software tools (Laidler et al., 2007). The cement mechanical properties were extensively studied under different conditions (Philippacopoulos and Berndt, 2001). However, there is seldom research on cement fatigue failure in the field of petroleum engineering.

While, in the field of mechanical engineering, there are some researches on metal fatigue failure (Placido et al., 1997; Teodoriu et al., 2008; Wu et al., 2008). And some people have done research on cement and concrete fatigue failure in the area of civil engineering. There are some experiments on the fatigue failure of portland cement concrete and paving concrete (Antrim, 1965; Joshi et al., 2004). In medical engineering, the probabilistic method was used to analyze the risk of failure of a cemented femoral component of a total hip replacement system and cement mantle of acetabular replacements (Nicolella et al., 2000; Nikolaus et al., 2007).

In this study, four failure modes, compressive failure, shear failure, tensile failure and fatigue failure were considered. There are two main objectives of this study. The first objective is to quantify the probability of failure of the cement in terms of specific failure modes. Model parameters such as the applied loads and material properties are modeled as random variables to account for the uncertainty and variability. The second objective is to identify the variables that contribute most to the probability of failure.

2. Methods

Two cement types were considered in this study. One is the unmodified Class G/40% silica flour (brittle cement) and the other is elastic cement.

Risk of failure was calculated based on the performance function of the type:

$$g(X) = R(X) - S(X) \quad (1)$$

where $R(X)$ is a random function describing the “resistance” or strength of the component or constituent, $S(X)$ is the response of the structure, also a random variable, and X is the vector of

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http://dx.doi.org/10.1016/j.petrol.2013.04.011

Nomenclature

c	cement cohesion, MPa
E	Young's modulus, GPa
N_f	load cycles, dimensionless
J_c	specific heat of water at constant volume, J/kg K
k_{fe}	effective thermal conductivity of the formation, W/m K
p_e	reservoir pressure, Pa
p_w	wellbore pressure, Pa
q_w	water injection rate, m^3/s m
r	radial co-ordinate, m
r_e	boundary radius, m
σ_{rr}	the radial stress, Pa
$\sigma_{\Theta\Theta}$	hoop stress, Pa
$\sigma_{r\Theta}$	shear stress, Pa
σ_s	compressive strength, Pa
σ_t	tensile strength, MPa
ω	cement friction angle, radian
ρ_w	density of injection fluid, kg/m^3
X	vector of random variable

random variables. A negative or zero $g(X)$represents a failure event. p_f is the probability of failure defined as

$$p_f = p(g(X) \le 0) \tag{2}$$

2.1. Solution to cement stresses

Stresses for plane linear elasticity problems, with reference to a polar co-ordinate system $O(r, \theta)$, are given in the following equation in terms of potential $\Phi(z)$ and $\Psi(z)$ of the complex variable $z = x + iy$:

$$\sigma_{rr} + \sigma_{\theta\theta} = 2[\Phi(z) + \overline{\Phi(z)}] \tag{4}$$

$$\sigma_{\theta\theta} - \sigma_{rr} + 2i\sigma_{r\theta} = 2\frac{z}{\overline{z}}[\overline{z}\Phi'(z) + \Psi(z)] \tag{5}$$

According to the boundary condition, the solution is expressed as

$$\Psi^{(k)}(z) = D^{(k)} + \frac{F^{(k)}}{z^2} + \frac{G^{(k)}}{z^4} \tag{6}$$

$$\Phi^{(k)}(z) = A^{(k)} + \frac{B^{(1)}}{z^2} + C^{(k)}z^2 \tag{7}$$

k =1 ,2, 3. 1 stands for casing; 2 stands for cement; 3 stands for formation.

The partial differential equation (Fagley et al., 1982) used to describe the wellbore heat transfer is

$$\frac{1}{r}\frac{\partial}{\partial}\left(rk_{fe}\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_{fe}\frac{\partial T}{\partial r}\right) - \frac{q_w \rho_w C_w}{2\pi r}\left(\frac{\partial T}{\partial r}\right) + \frac{q_w(p_w - p_e)}{2\pi r^2 J_c \ln(r_e/r_w)} = (\rho C)_e \frac{\partial T}{\partial r} \tag{8}$$

From Eqs. (4)–(8), given bottomhole pressure, formation temperature, formation pressure and material properties, the radial stress σ_{rr}, hoop stress $\sigma_{\theta\theta}$ and shear $\sigma_{r\theta}$ can be solved. The solutions to A, B, C D, F, and G can be found (Atkinson and Eftaxiopoulos, 1996).

2.2. Cement failure modes

1. Compressive failure

$$g_1(\sigma, \sigma_s) = -\sigma + \sigma_s \tag{9}$$

2. Shear failure

$$g_2(\tau, c, \sigma_s, \omega) = -\tau + c + \sigma_s \tan\omega \tag{10}$$

3. Fatigue failure

For brittle cement, $g_3(N_f, \sigma, \sigma_s) = -Log(N_f) - 0.082\frac{\sigma}{\sigma_s} + 8.48$ (11)

For elastic cement, $g_3(N_f, \sigma, \sigma_s) = -Log(N_f) - 0.109\frac{\sigma}{\sigma_s} + 11.6$ (12)

4. Tensile failure

$$g_4(\sigma_{tensile}, \sigma_t) = -\sigma_{tensile} + \sigma_t \tag{13}$$

3. Field applications

The well is located in Cameron, Louisiana. As shown in Fig. 1, Well depth 1829 m; formation pore pressure gradient, 0.01074 MPa/m; overburden pressure gradient, 0.02262 MPa/m; formation horizontal principal stress, 30 MPa, 33 MPa; fracture

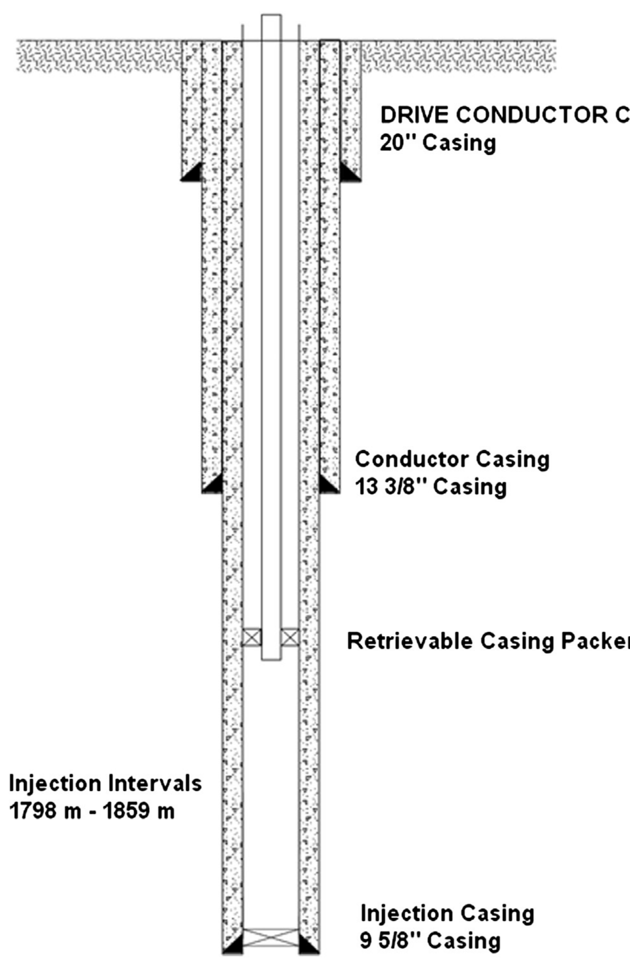

Fig. 1. Wellbore geometry.