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Development of a 3D numerical model for quantifying fluid-driven interface debonding of an injector well

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ABSTRACT

Interface debonding is considered as a major reason for loss of well integrity of a CO_2 injector. In this work, a 3D numerical model is developed for simulation of a fluid-driven debonding fracture using the coupled pore pressure cohesive zone method. The equations used in the method are described. The method is validated by numerically reproducing the results of an interface debonding experiment reported in the literature. The 3D model is used to quantify the propagation pressure and the geometry of the debonding fracture in a vertical well. The effects of several key factors in the development of debonding fractures are investigated. The results show that fracture propagation pressure is more sensitive to horizontal stress than to casing pressure. The presence of initial defects at the interface can significantly reduce the propagation pressure and the debonding fracture tends to develop vertically, rather than circumferentially at the interface. The results also demonstrate that the debonding growth is highly influenced by the cement stiffness, critical strength and toughness of the interface, illustrating the importance of appropriate cement design. The method proposed herein presents a useful step towards prediction of loss of well integrity due to interface debonding, and provides improved guidance for cement selection and injection optimization.

1. Introduction

Well integrity, always of importance, is becoming more so because of increasing environmental concerns and regulatory activities. It is particularly vital for the long-term safe and ecologic storage of carbon dioxide (CO_2) (Bai et al., 2015; Loizzo et al., 2011; Watson and Bachu, 2009; Zhang and Bachu, 2011). Loss of well integrity can lead to costly remedial operations and severe environmental contamination (Jo and Gray, 2010). The cement sheath is the heart of well integrity. It is expected to ensure well integrity by providing zonal isolation and support for the casing throughout the life of a well, from well construction through hydrocarbon production and post-abandonment (Gray et al., 2009). A successful cementing job is expected to result in complete zonal isolation, without leaving any leakage pathway in the annulus between casing and formation. Unfortunately, this goal is not always achieved, and leaks from a well may occur during the life of a well (Fourmaintraux et al., 2005).

Due to the low permeability of cement, leaks are believed to occur only through defects within the cement sheath. These defects may include mud channels due to poor cement placement, chimneys caused by gas or brine breaking through cement during the setting process, cracks within the cement resulting from excessive stress in the cement and, more importantly, debonding at cement/casing or cement/formation interfaces (Lecampion et al., 2013; Loizzo et al., 2011). In this study, attention is focused on the leakage pathway due to debonding at the casing/cement or cement/formation interface. Interface debonding can be caused by variation of wellbore pressure and/or temperature during the life of a well (Lecampion et al., 2013; Zhang and Bachu, 2011). A likely source of such an interface debonding is the excessive pressure build up associated with fluid injection operations, e.g. CO_2 injection (CO_2 is usually in the supercritical fluid phase or dissolved in water) (Loizzo et al., 2011; Lecampion et al., 2013). The interface debonding occurs when the fluid pressure at the interface overcomes the normal stress and the bonding strength of the interface.

In a cased and cemented well, fluids are usually injected into the formation through perforations (Fig. 1). Perforation operations provide pressure communication between the wellbore and the interface. They may also create small defects at the interface near the perforated sections, which may facilitate the initiation of debonding fractures. As shown in Fig. 1, at the bottom hole below the packer, the casing and interface are subjected to the same fluid pressure during injection via the perforations. However, due to the difference in the stiffness of

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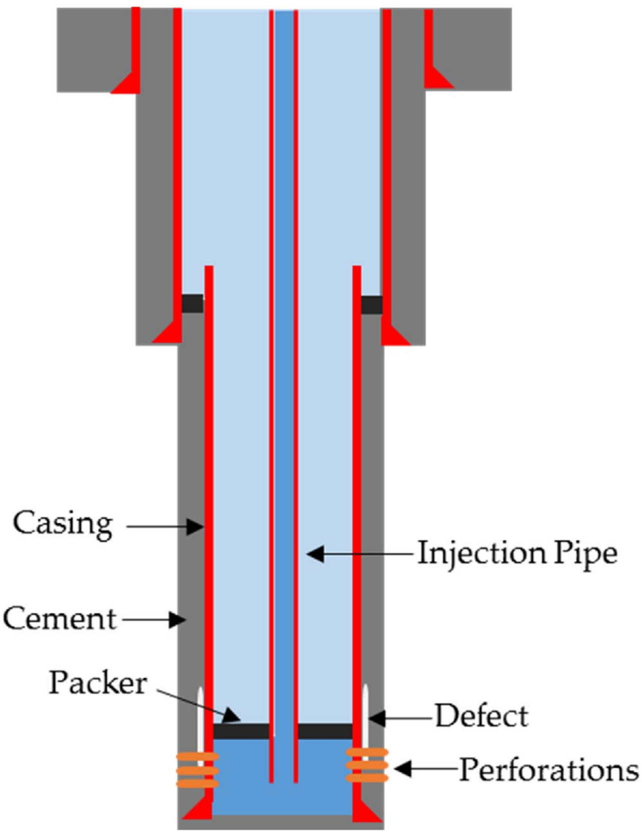

Fig. 1. Schematic of a typical cased and cemented well for fluid injection operations (Modified after Lecampion et al., 2013).

casing and cement, the normal clamping stress at the casing/cement interface (resulting from casing pressure) can be much lower than the fluid pressure within the interface, which may also facilitate fracture growth. The casing pressure above the packer is even lower than that in the perforated section. Therefore, once the fluid-driven debonding fracture starts to grow, it may easily extend upward. In this work, a 3D numerical model is used to quantify the development of the debonding fractures due to pressure build-up at the cement interface in fluid injection operations.

A few researchers have developed models to simulate cement interface debonding based on a number of simplifications, such as linearly elastic casing, cement and rock, and initially intact cement sheath (Bosma et al., 1999; Fleckenstein et al., 2001; Fourmaintraux et al., 2005; Gray et al., 2009; Pattillo and Kristiansen, 2002; Ravi et al., 2002; Shahri et al., 2005). However, laboratory tests performed on a Class-G cement system show that the cement is better characterized as a porous media, rather than a one-phase linear elastic material (Bois et al., 2012, 2011; Ghabezloo et al., 2008). Additionally, non-linear stress-strain behavior of the rock formation is important (Morita and Gray, 1980). When either the cement sheath or the rock formation in the vicinity of the wellbore exhibit non-elastic behavior, appropriate constitutive laws for correct description of cement and formation behavior are essential for cement sheath modeling (Bois et al., 2011; Gray et. al., 2009).

Most previous numerical studies on interface debonding did not consider initially existing defects at the cement interfaces. Such defects may be induced by perforation operations, poor mud removal, or cement shrinkage during hydration, (Bosma et al., 1999; Fleckenstein et al., 2001; Fourmaintraux et al., 2005; Gray et al., 2009; Ravi et al., 2002; Shahri et al., 2005). Additionally, most researchers have modeled interface debonding as a tensile or shear failure due to high local stress induced by the combined effects of field stress, casing pressure, and temperature changes. However, when an initial defect due to perforation operations or cement shrinkage exists at the cement interface, fluid can easily invade into the defect, leading to pressure buildup within the interface and fluid-driven debonding. Consequences of the interface debonding, such as uncontrolled inter-zonal flow and leakage of fluids to the surface, can result in severe operational troubles and substantial environmental pollution (Wang, 2014).

Gray et al. (2009) developed numerical models to investigate cement debonding by modeling the casing/cement interface as a contact condition, which may allow zero or some amount of tension transmission across the interface, corresponding to the cases with no bonding strength and finite bonding strength respectively. Bosma et al. (1999) and Ravi et al. (2002) modeled the cement interface as a layer of interface elements based on a Coulomb friction model. While such models may be satisfactory for analyzing interface debonding when there is no fluid invasion into the annular cracks after debonding, they cannot simulate the propagation of fluid-driven fractures along the interface, which requires fully-coupled modeling of the mechanical behavior of the casing/cement/formation system and fluid flow into and along the fractures.

Great progress has been made in fully-coupled modeling of fluid-driven fractures in porous media in the past decade, such as development of the coupled pore pressure cohesive zone method (CZM) and coupled pore pressure extended finite element method (XFEM) as implemented in the commercial code Abaqus (Kostov et al., 2015; Searles et al., 2016; Wang, 2015; Yao et al., 2010). These modeling techniques in Abaqus successfully account for several key factors of fluid-driven fractures in porous media, including fluid flow within the fracture, pore fluid flow in the porous media, deformation of porous medium, and fracture propagation (Zielonka et al., 2014). However, these techniques have not been applied to model well integrity problems until recently. Wang and Taleghani (2014) applied the existing pore pressure CZM in Abaqus to investigate debonding at the casing shoe due to excessive pore pressure charged by deeper kick zone or fluid migration along damaged formation.

The work presented here is another implementation of the pore pressure CZM in Abaqus to interface debonding modeling. The numerical approach in this work is similar to that used by Wang and Taleghani (2014), but the model assumptions, interpretation methods, and specific focus are substantially different. Whereas Wang and Taleghani (2014) mainly investigated the effects of interface properties on the debonding fracture, the current study extends to the simulation of non-uniform debonding fractures with various in-situ stress conditions and pre-existing cracks at the cement interfaces. In addition, while Wang and Taleghani (2014) mainly focused on the development of the fracture geometry, this study also investigates the dependence of the propagation pressure of the debonding fracture on various factors. To our knowledge, this paper is the first reported endeavor on applying the pore pressure CZM technique to model dynamic cement debonding from pre-existing interface cracks of different sizes. The main interest is cement debonding of an injector due to excessive pressure buildup at the cement interface during fluid injection, which may be the type of operation most likely to disrupt well integrity. In the scope of CO_2 storage, modeling of the interface debonding is of prime importance for understanding the fundamental mechanism of the debonding process and providing guidance for design of CO_2 injection to ensure well integrity. It should be noted that the model developed in this study takes into account the porous and plastic features of the cement and rock which have proven important for the study of well integrity problems (Bois et al., 2012, 2011; Ghabezloo et al., 2008; Gray et al., 2009). However, a comparison against a simpler case without considering these features is not the focus of the current work, and the corresponding comparison results are not provided in this paper. Refer to Bois et al. (2012) and Gray et al. (2009) for discussions of the importance of these factors on well integrity.

In the following, with the main objective of quantifying behavior of the debonding fractures along a wellbore annulus, first the main