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Above zone pressure interpretation for leaky well characterization and its identification from leaky caprock/fault

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ABSTRACT

Pressure transient analysis has long been used for reservoir characterization. Above-zone (AZ) pressure has been recently investigated for inferring leakage pathway characteristics in leakage events from subsurface injection operations. The recorded pressure in the AZ should be purely related to leakage and therefore it can be safely inverted to deduce leakage characteristics. It is crucial to evaluate fluid leakage through abandoned wells to plan for further measurements of leakage prevention. However, the recorded AZ leakage signal may not be related to leaky well(s). Therefore, identification and spatial investigation of well leakage is required for leakage evaluation. In this paper, we propose a pressure interpretation method for early detection of leaky pathways, applying two observation points in the AZ. We distinguish leaky well, fault and caprock based on their corresponding flow regime identification. We show that the pressure difference of the two observation wells can be applied as a proxy for unknown leakage rate, which is crucial for leakage identification as well as characterization. Results show that the estimated location of the leaky well, leakage coefficient, and the leakage rate are in good agreement with the actual values. The estimated leakage coefficient of the leaky well can be used to evaluate well leakage in multiphase systems such as carbon dioxide leakage in deep saline aquifers.

1. Introduction

Undesirable leakage from underground sedimentary formations is a matter of considerable concern due to implications for water resources contamination and greenhouse gas emissions (Benson and Orr, 2008; Birkholzer et al., 2009; Blackford et al., 2009; IPCC, 2005; Keating et al., 2013; Lu et al., 2010; Pacala, 2003; Siirila et al., 2012). Leakage in underground formations can remain undetected for a long period. This work aims to provide an identification method for early detection of leakage from injection zone to overlying formations. The identification method is based on the pressure monitoring in a permeable above zone (AZ) supposedly separated from the injection zone by a confining layer.

Deep saline aquifers are used for underground disposal/storage of fluids. Leakage of the injected fluids from the injection formation may adversely affect underground environment, especially underground fresh water resources. The contamination can be a consequence of native fluid leakage as well as injected fluids (Damen et al., 2006; Little and Jackson, 2010). For instance, leakage of brine during CO_2 injection into saline aquifers can affect the shallow resources of fresh water. CO_2 can contaminate fresh water resources and may impact pH of the native fluids (e.g. brine) and can result in dissolution and movement of minerals (de Orte et al., 2014; Harvey et al., 2012).

In addition, natural gas is stored in underground formations to be produced at specific times to satisfy demands (Katz and Tek, 1981). Leakage of injected natural gas to shallower formations as well as the surface may occur in storage projects (Lewicki et al., 2007). For instance, a leaky fault accommodated leakage in the Leroy natural gas storage project in Wyoming (Chen et al., 2013). Natural gas leakage would lead to unavailability of a portion of the injected gas for reproduction as well as environmental damages (Laier, 2012; Miyazaki, 2009).

The existence of the naturally occurring potential leaky structures may not be a major problem during the natural accumulation of fluid in the reservoirs. However, the overpressure caused by injection operations would enhance the leakage risk (Rutqvist et al., 2007). Moreover, injection pressurization may be associated with induced seismicity that can be felt by the general population, and may cause damages (Ellsworth, 2013; Keranen et al., 2013). Induced seismicity can also damage the sealing capacity of existing potential leakage pathways including wells, faults, and caprock (Cappa and Rutqvist, 2011; Wiprut and Zoback, 2000).

Plugged and Abandoned (P&A) wells are examples of leakage pathways that may be conduit for fluid migration from confined

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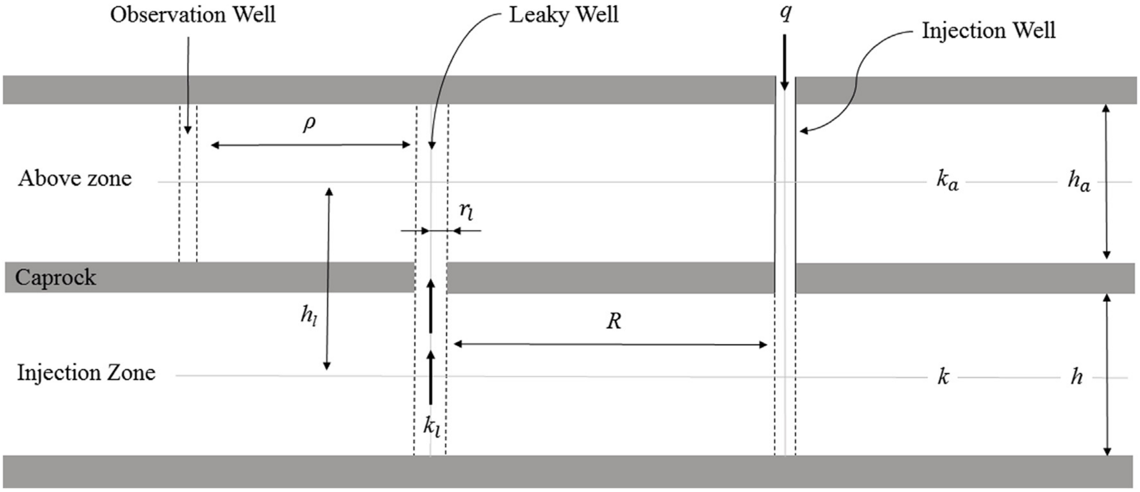

Fig. 1. Schematic representation of the two-layer system with leaky well. This schematic applies for fault leakage system with the replacement of the leaky well with leaky fault. For leaky caprock system, the leaky well is removed and a weakness in the caprock should be considered.

permeable formations (Ebigbo et al., 2007; Jordan and Carey, 2016; Watson and Bachu, 2009). Abandoned wells should be plugged according to standard regulations to prevent undesirable hydrodynamic connection between the sequential layers intersected by the well. Cementing materials used during the P&A process normally have very low permeability. However, the permeability can be changed by cement degradation over a long time. Further, the interfaces of cement, rock matrix and casing can be the weak points of leakage for a plugged well (Bachu and Bennion, 2009; Wojtanowicz, 2016). CO_2 can make decomposition reaction with cement after flowing inside the cement matrix (Scherer and Huet, 2009). In addition, the low pH brine caused by CO_2 dissolution can corrode the sealing cement of abandoned wells. The acidified brine may affect the cement especially if the acid remains in contact with cement for several years (Scherer et al., 2015; Toews et al., 1995). Completion failure of the injection well can also be a reason for well leakage.

Leaky caprocks and leaky faults are two other possible leakage pathways that can cause significant hydraulic connection between confined sedimentary formations (Annunziatellis et al., 2008; Barton et al., 1995; Chen et al., 2013; Evans et al., 1997; Hermanrud and Bols, 2002; Leith et al., 1993; Sibson, 1977). A fault is a planar interface that can be permeable across and along the fault plane with different permeabilities in different directions. A fault generally consists of a low permeability core surrounded by high permeability damaged zones. The permeability of the damaged zone is controlled by the fractures induced during fault displacement (Agosta et al., 2007; Billi et al., 2003; Bruhn et al., 1994; Caine et al., 1996; Caine and Forster, 1999; Chester et al., 1993; Rawling et al., 2001). In addition to leaky fault and well, leakage can occur through a permeable region in a seal/low-permeability caprock layer. The induced stress caused by overpressure can damage the caprock seal especially during the injection (Hermanrud and Bols, 2002; Ingram and Urai, 1999; Selvadurai, 2012; Sibson, 2003).

Pressure transient interpretation is a robust approach to identify fluid leakage in the subsurface. In the injection zone, the leakage-induced pressure signals are combined with stronger signals caused by injection. The AZ pressure monitoring is more reliable for leakage identification since it should be merely related to leakage. Analytical approaches are easy to apply and can provide direct relationships between hydraulic characteristics of the system and pressure signal. Numerical methods can also be used to investigate the fluid leakage but it is computationally expensive. In addition, all system properties are required for a numerical simulation but the system can be analyzed with a reduced number of (dimensionless) parameters identified by analytical models. Most pressure and rate transient methods in reservoir characterization stem from analytical models.

Several analytical models were introduced to quantify leakage through different types of pathways. Javandel et al. (1988) developed an analytical solution to model pressure response to a leaky well in a multi-layer system. They considered an observation well in the injection layer and assumed pressure of the upper layer is constant throughout. Avci (1994) developed an analytical solution for well leakage to an upper layer considering the upper layer's resistance to flow. Cihan et al. (2011) developed a multilayer analytical solution for leaky wells. Zeidouni and Vilarrasa (2016) introduced a real time solution for pressure perturbation due to a leaky well in a two-layer system separated by a confining layer. They proposed a method to locate the leaky well by considering three observation wells in the AZ. Zeidouni (2014) presented an analytical solution for well leakage in a laterally bounded multilayer system. Analytical models were also developed to examine the other leaky pathways. Leakage through a low-permeability caprock is modeled as diffuse leakage (Cheng and Morohunfola, 1993; Cihan et al., 2011). Leaky faults are modeled as planar discontinuities in the reservoir (Anderson, 2006; Shan et al., 1995; Zeidouni, 2012, 2016).

A primary step for leakage characterization is identification of the major leakage pathways and evaluation of their leakage potential. In this study, we first present a characterization procedure for leaky well system based on the AZ pressure. Location and leakage coefficient of the leaky well and the leakage rate are estimated considering two observation wells in the AZ. Next, we extend the leakage identification to distinguish the leaky caprock, leaky fault and leaky well according to the pressure response. The identification method is based on the diagnostic plots of the specific flow regimes. The identification and characterization procedures are applied to example problems for demonstration.

2. Methodology

Fig. 1 shows schematic of the leaky well physical model. The two-layer system is the same for the leaky fault and leaky caprock. In leaky fault system, the leaky well is replaced with the leaky fault. For the leaky caprock, there is a permeable region in the caprock layer instead of leaky well (Fig. 1). The leaky pathway connects the AZ to the injection zone while these zones are otherwise separated by the confining layer (caprock). In this study, the leakage problem is thought of as injection into the single-layer AZ through the leaky pathway. In order to identify the leakage by this approach, we need to apply deconvolution