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Technical Note

Deformation characteristics of a clayey interbed during fluid injection

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ABSTRACT

Surface deformation due to fluid withdrawal has long been observed at the surface above aquifers and oil reservoirs. Uplift associated with fluid injection has also been observed. Although the processes of subsidence and uplift are reversible in a poroelastic setting, the presence of clayey interbeds can result in ground deformation behavior non-reversible because of their low permeability and nonlinear behavior. In this investigation a Cam clay model is used in conjunction with a poroelastic model to simulate the presence of a laterally extensive lens-shaped clayey interbed in a sandstone aquifer during fluid injection. Spatial and temporal changes associated with this interbed during aquifer pressurization are captured and can be clearly differentiated from the deformation of the surrounding poroelastic aquifer formation. Results for pore pressures and ground surface deformation patterns can be categorized into three distinct time intervals: an early time interval where the aquifer is pressurized but not the interbed leading to a lower region above the interbed; an intermediate time interval in which the interbed pressures slowly increase, approaching the pressure of the adjacent aquifer, leading to a potentially large surface uplift above the interbed; and a late time interval in which pressure equilibration is achieved between the interbed and aquifer and a highly non-symmetrical irregular surface deformation pattern results, which may be higher or lower than the background depending on the interbed characteristics. Reservoir configuration is found to be an important factor influencing ground deformation behavior, with more obvious deformation always occurring in a laterally confined aquifer as opposed to a laterally infinite aquifer.

1. Introduction

Land deformation due to fluid withdrawal or injection has long been observed over many oil reservoirs and aquifers systems (Tolman and Poland, 1940; Yerkes and Castle, 1969; Vasco et al., 2001; Bell et al., 2002; Teatini et al., 2011a,b). As the prospect of CO_2 sequestration progresses as an important environmental issue, gaining knowledge about aquifer-system response to waste storage becomes vitally important (Vasco et al., 2010). With the development of sophisticated surface monitoring techniques such as InSAR and GPS, careful monitoring of surface deformation signals during fluid injection can yield critical information about the geometric configuration and characterization of the host reservoir (Fielding et al., 1998; Vasco, 2004).

For historical reasons, the literature associated with land subsidence due to fluid withdrawal is far more abundant than those associated with land uplift due to fluid injection. In a poroelastic hypothetical framework, these two processes are opposite to each other and reversible. Exceptions include formations with high clay content because clays often result in non-reversible and nonlinear deformation behavior. These systems are more difficult to evaluate than purely elastic systems because a hydrodynamic (time) lag response typically occurs in systems containing clayey interbeds due to their low permeability. Consequently, their response to an imposed confining stress is dependent on the preconsolidation stress history because their virgin compaction curve and rebounding curve often do not coincide.

In this investigation an interbed refers to a relatively thin lens-shaped unit composed of fine-grained clay material with a much lower permeability and relatively higher porosity than the surrounding host aquifer formation, which is composed of sandstone (Figure 1).

The hydrodynamic lag has been observed during fluid withdrawal as the clayey interbeds drain more slowly than the surrounding coarser aquifer material. This leads to a time-delay between the extraction of the groundwater and the occurrence of land subsidence (Shearer, 1998). The time lag for consolidation can range widely from several days to many decades or even longer (Bell et al., 1986; Hoffmann et al., 2001; Li et al., 2006; Shi et al, 2007).

This hydrodynamic lag effect may also be expected during fluid injection, but it is unclear whether the mechanics of the deformation response will be similar to that of groundwater withdrawal. The goal of this technical note is to investigate the hydrodynamic lag and the surface deformation response caused by clayey interbeds during fluid injection and to correlate the deformation response with the pore pressure evolution in both the clayey interbed and the aquifer.

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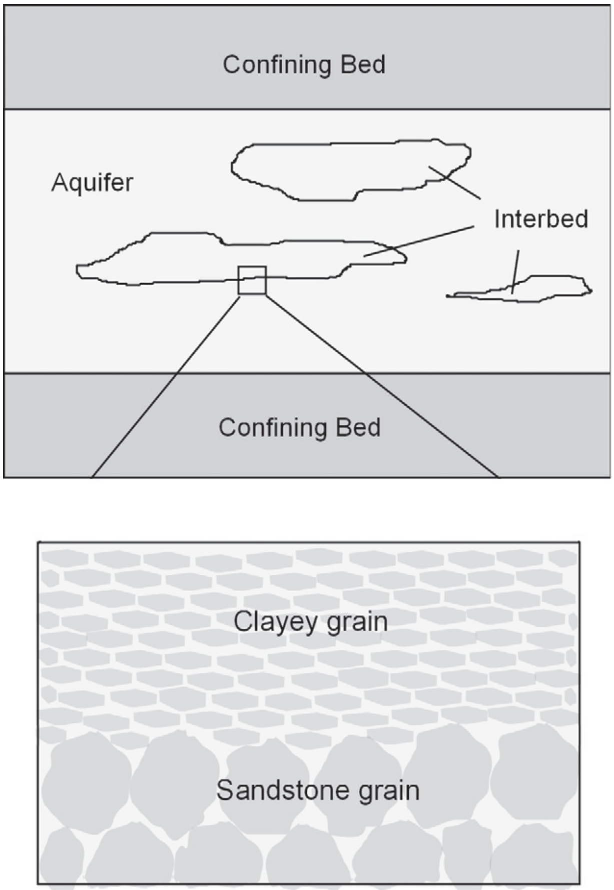

Fig. 1. Regional and pore-scale illustrations of clayey interbeds within an aquifer system. (Modified after Leake, 1990).

2. Properties of clayey rock

Clayey rocks (clays, claystone, shale, mudstone) represent an important constituent of sedimentary basin fill (Hildenbrand and Krooss, 2003). Many of these rocks are considered to be soft rocks that lie between hard soils and (moderately) strong rocks. The distinction between soil and rock is to a certain extent arbitrary because the processes of weathering and diagenesis are gradual (Nova, 2010). The boundaries between soils and rocks as set by the uniaxial unconfined compressive strengths vary by different organizations and researchers. These strength values can range from less than 1 MPa to that over 25 MPa (Bieniawski, 1973; IAEG, 1979; BSI, 1981; ISRM, 1982; Hawkins and Pinches, 1992).

Laboratory testing on some clay or clayey rocks show that these rocks' permeability can range greatly from 1 nD to 1 mD (values on the lower end are more common), their porosity can range from 0.03 to 0.55, Young's modulus can range from 0.1 to 30 GPa and Poisson's ratio can range from 0.13 to 0.38 (Neuzil, 1994; Giraud and Rousset, 1996; Dewhurst et al., 1998; Horsrud et al., 1998; Gale et al., 2007; Gasparre et al., 2007; Hight et al., 2007; Loucks and Ruppel, 2007; Engelder et al., 2009; Sarker and Batzle, 2010; Yang and Aplin, 2010; Zhou et al., 2010; Fidler, 2011; Vermylen, 2011; Eshkalak et al., 2013). One may note that their Poisson's ratios that were acquired in the lab may be undrained ratios in some cases. Their permeability also exhibits a higher degree of anisotropy (Zhang, 2005). For example, the ratios of the permeability measured parallel to bedding over those measured perpendicular to bedding for the Wilcox shale are greater than 10 (Kwon et al., 2004), whereas this ratio is only 4 for Berea sandstone (Zoback and Byerlee, 1976) and 2.2 and 1.2 for Crab Orchard sandstone and Bentheim sandstone, respectively (Benson et al., 2005; Louis et al., 2005).

The mechanical behavior of stiff soil and clayey rocks during loading and unloading are similar in many aspects. This includes an initial stiff response until the normal compression line is reached, followed by an increase of the state boundary surface and followed then by a stiff response upon unloading. Hence, instances occur in which the behavior of clayey rocks can be better described within the theoretical framework of a critical state model of soil mechanics (Vukadin, 2007). A Cam clay model is used in this investigation to simulate the hydromechanical response of a clayey interbed during fluid injection. A short introduction on the mathematical framework for the Cam clay model follows.

3. Theoretical background

Several different approaches can be used to mathematically characterize aquifer heterogeneity. One approach is to use Eshelby's inclusion theory (Eshelby, 1957; Mura, 1982; Segall and Fitzgerald, 1998), which is applicable for an aquifer embedded with clayey interbed as investigated in this paper.

In such a system, pore pressures increase differently in the different hydrologic units during fluid injection due to the different permeability of each unit, which leads to differing stain histories of each unit during the pressure change. Because clayey formations behave differently than the coarser-grained aquifer formation, we simulate an interbed as an inclusion in an otherwise homogenous poroelastic aquifer formation using a Cam clay model.

3.1. Cam clay model

The ability of the Cam clay model to accurately simulate the behavior of a clayey formation has been demonstrated in the past (e.g. Helwany, 2007). A Cam clay model is chosen because it can simulate the entire range of expected behaviors of plastic materials (clays) that include (1) a yield criterion that predicts whether the material will respond elastically or plastically in response to a loading increment, (2) a strain hardening rule that controls the shape of the stress–strain response during plastic straining, and (3) a plastic flow rule that determines the direction of the plastic strain increment caused by a stress increment (Roscoe et al., 1958; Alonso et al., 1990). The total volumetric strain rate in the clayey inclusion $d\varepsilon_{vol}^{inclusion}$ can be decomposed as:

$$d\varepsilon_{vol}^{inclusion} = d\varepsilon_{vol}^{el} + d\varepsilon_{vol}^{pl} \tag{1}$$

where $d\varepsilon_{vol}^{el}$ and $d\varepsilon_{vol}^{pl}$ represent elastic (recoverable) strain rate and plastic (non-recoverable) strain rate, respectively. The loading function retained to account for the yield surface of clays is expressed in the form (Coussy, 2004):

$$2f(\sigma, q, \sigma_{co}) = \left(\sigma - \frac{1}{2}\sigma_{co}\right)^2 + \frac{q^2}{M^2} - \frac{1}{4}\sigma_{co}^2 \tag{2}$$

where σ is equivalent pressure stress (or mean effective stress), q is the deviatoric stress, σ_{co} is the maximum effective stress (or the preconsolidation stress) as used in Eq. (2), and M is a material constant. A typical loading–unloading curve for a Cam clay model is shown in Fig. 2.

Two key parameters of the Cam clay model are identified in Fig. 2, i.e., w (logarithm plastic bulk modulus) and m (logarithm elastic bulk modulus). w is the slope of the normal consolidation line, defined by $w = -\,de/d(\ln\sigma)$, and m is the slope of the unloading line, defined by $m = -\,de^{el}/d(\ln\sigma)$, where e is void ratio and e^{el} is its elastic component. The value of m depends on the type of clay and usually ranges between 5% and 25% of the value of w (Nova, 2010).

In this investigation, we focused on the coupled hydrological–mechanical processes of a clayey interbed during fluid injection. The