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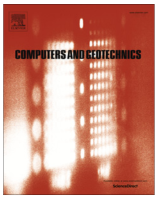

Research Paper

Estimation of the surface uplift due to fluid injection into a reservoir with a clayey interbed

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ABSTRACT

Injecting fluid into subsurface reservoirs is a hydromechanical coupling process that can induce heaving of the ground surface. The presence of clayey interbeds in the reservoir can have considerable influence on the surface uplift. We used a numerical method to investigate this process. We found that different locations have different impacts on the surface uplift. We applied the orthogonal experimental design using the Taguchi method for extensive parametric analysis and determined the most influential factor. Finally, we analyzed the low-permeable effect of the interbed due to its low permeability, compared to the reservoir.

1. Introduction

As is well known, extraction of underground fluid (e.g., water, oil, or gas) can cause land subsidence [1–3]. The induced subsidence results in a series of serious problems for the environment and infrastructure on or in the ground [4]. Therefore, a large number of observations and studies about this issue have been successfully conducted by many researchers [5,6]. As an inverse process, injecting fluid into the underground formations often causes surface uplift [7–13]. Since the 1940s, for the various purposes of the development of human society, a variety of underground fluid (water, vapor, N_2, CO_2, etc.) injection projects have been widely developed, such as CO_2-enhanced oil recovery (CO_2-EOR) [14,15], CO_2 geological storage combined with deep saline water/brine recovery (CO_2-EWR) [16], aquifer storage and recovery [17], cyclic steam stimulation [18], the use of CO_2 as the working fluid in enhanced geothermal systems (CO_2-EGS) [19,20], and CO_2 capture and storage (CCS) [21,22]. All these activities involve injecting fluid into subsurface formations, which can cause the ground surface to heave [23,24].

There is far less concern about the surface uplift caused by fluid injection than the surface subsidence caused by underground fluid extraction. There are several reasons for this. First, in most cases measuring surface displacement was not a priority, in part due to the large cost of leveling surveys. Second, in other instances the uplift was so small that no environmental hazards were caused and no monitoring scheme was really needed, or the area involved was quite limited with no reported or even expected damage to engineered structures or infrastructure [13]. However, investigating this can be of interest. One important reason is that using inversion analysis applied to data on the surface uplift can help us understand the fluid storage mechanisms and the characteristics of the reservoir [25]. Thanks to the emergence and application of Interferometric Synthetic Aperture Radar (InSAR) technology, it is possible to observe small surface deformations, which has aroused the research interests of many scholars [9,26–29].

Some researchers have studied related theories on the surface uplift induced by fluid injection and proposed several theoretical calculation methods [7,10,11,13]. However, almost all of the methods treat the reservoir as a homogeneous elastic body without any inclusions. In fact, reservoirs are always complicated heterogeneous bodies. For example, clayey interbeds may exist in the reservoir and often result in non-reversible nonlinear deformation behavior. Furthermore, minor faults and fractures may be present in the reservoir, rendering it discontinuous. These features can influence the distribution of the pore pressure and cause fracture openings or faults to react during fluid injection, which causes changes in the surface uplift. In the In Salah injection well KB-502, a double-lobe uplift pattern was observed in the ground-deformation data [30]. Then, the analytical calculation methods become less applicable to calculate the surface uplift and

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numerical simulation becomes a better choice for solving these problems. For example, Rinaldi et al. used the coupled fluid flow and geomechanical simulator TOUGH-FLAC for a detailed analysis of the double-lobe uplift of the In Salah injection well KB-502 [30]. Fei et al. developed an in-house program named "AEEA Coupler" that linked two software packages, i.e., ABAQUS and ECLIPSE, to analyze the interaction between CO_2 geological storage and underground coal mining. They found that the combined activities achieve a surface subsidence reduction comparable to that of just coal mining [31].

The existence of clayey interbeds in the reservoir can result in great heterogeneity and exert a significant impact on the surface uplift during fluid injection. It is very difficult to evaluate the induced surface uplift using analytical calculations because of the plastic deformation behavior of the clays. Zhou and Burbey investigated the hydrodynamic lag and the surface deformation response caused by clayey interbeds during fluid injection [32]. However, there are some problems that need to be studied further: (1) what effect do the location and aspect ratio of the interbed have on the surface uplift during fluid injection; (2) what effects do the mechanical properties of the interbed have on the surface uplift; and (3) which of the properties is most influential. In this paper, based on the work by Zhou and Burbey [25], a series of numerical experiments using the orthogonal experimental design method were designed to answer the above questions. The low-permeable effect of the interbed due to its low permeability, compared to the reservoir, was also studied in the paper.

2. Analytical solutions

Fluid injection is a process of hydro-mechanical coupling, with fluid flowing through porous media. When pressure increases the effective stress becomes lower and the reservoir expands. The expansion of the reservoir causes the porosity and permeability to change, thereby affecting the flow and its pressure. Effective stress theory offers a common explanation for the induced surface uplift during fluid injection. Injecting fluid into a reservoir leads the reservoir to experience expansion deformation. Then the expansion propagates to the ground surface, causing the surface uplift. Another explanation involves shear dilation, which can be easily understood with the aid of the schematic Mohr representation of the stress state shown in Fig. 1. The vertical effective stress is reduced due to the increase in pore pressure during injection, leading to the Mohr's circle moving leftward. If the Mohr's circle intersects the failure line, a shear failure may occur. If it crosses the τ-axis, a tensile failure may take place. The failure can result in new migration paths, and the shear can induce an increase in the volumetric strain, which leads to the expansion of the reservoir and the uplift of the surface [13]. Additionally, reactivation of existing fractures and faults are much more likely to occur before failure. However, these two explanations cannot be used for quantitative calculation of the surface uplift.

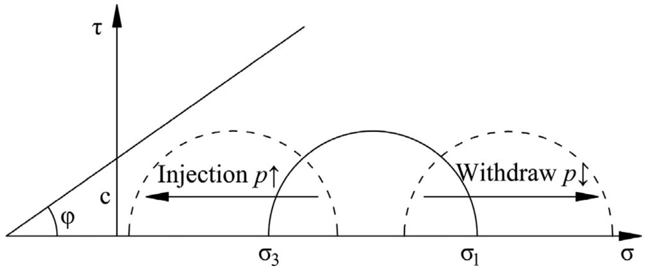

Fig. 1. Mohr-Coulomb circle (after [13]). c is the cohesion (Pa) and φ is the friction angle (rad), σ-axis is the normal effective stress and σ_1 and σ_3 are the maximum and minimum effective principal stresses, respectively. The injection of fluid into the reservoir causes a decrease in the effective stress, resulting in the circle moving leftward and possibly intersecting the failure line or crossing the τ-axis, which can cause shear failure or tensile failure, respectively. Withdrawing fluid from the reservoir is the reverse process, moving the circle rightward.

There are several typical approaches, as follows.

2.1. One-dimensional approach

Assuming a thin and laterally extensive reservoir, Fjær et al. proposed a one-dimensional uplift model (Fig. 2) to estimate the uplift [33]:

$$\Delta h_r = \left[\alpha \frac{(1+v)(1-2v)}{(1-v)E}\Delta p\right] h_r \tag{1}$$

where Δh_r is the vertical expansion of the reservoir, m; h_r is the thickness of the reservoir, m; α is Biot's coefficient; v is Poisson's ratio; E is Young's modulus, Pa; and Δp is the change in pore pressure, Pa.

The basic concept of this method involves the use of the vertical expansion of the reservoir to estimate the surface uplift. It is a rough approximation that can be used to estimate the order of magnitude of the uplift. However, this method has some limitations. It assumes that the horizontal displacement is negligible and that the overburden rock does not restrict the expansion of the reservoir. Thus, the value of the uplift will likely to be overestimated. More importantly, it cannot be used to calculate the uplift distribution at different locations on the surface. It also cannot be applied to estimate the influence of a clayey interbed in the reservoir on the surface uplift due to the inelastic and nonlinear deformation behavior of the clay. Therefore, this approach cannot be used to estimate the surface uplift due to fluid injection into a reservoir with a clayey interbed.

2.2. Elastic plate approach

Selvadurai used an elastic plate approach to calculate the uplift of the surface rock layer [11].

As shown in Fig. 3, the disc-shaped storage reservoir is assumed to be embedded in an elastic half space, while the surface rock layer is assumed to be a thin plate. The pressurized storage reservoir region is represented by a circular disc-shaped zone. The surface layer undergoes bending deformation, and the deflection $w(r)$ is the surface uplift.

The modeling of the problem focused on the elastostatic analysis of the interaction between the surface rock layer and the storage reservoir. Two cases of the interaction were considered: fully bonded and frictionless contact. The latter assumed that there could be relative slip between the surface rock layer and the storage reservoir, but there was continuity of normal traction and normal displacement at the interface.

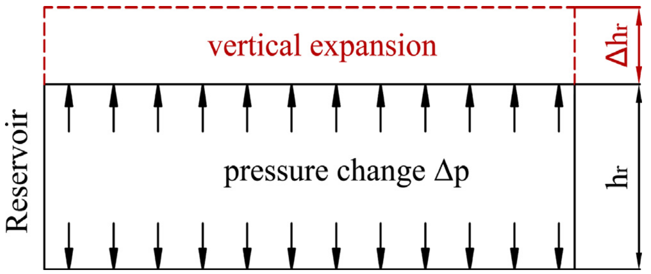

Fig. 2. Vertical expansion of the reservoir due to pore pressure. Δp is the change in pore pressure, Δh_r is the vertical expansion of the reservoir, and h_r is the thickness of the reservoir.