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Review article

A review of shale swelling by water adsorption

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ABSTRACT

Due to the improvement of drilling and recovery techniques, shale gas exploration has developed rapidly over the past ten years, and problems that have arisen have attracted increasing attention. Swelling of shale with the adsorption of water is one of the leading problems for shale gas exploration, as it causes wellbore instability and shale formation collapse. The main objective of this study is to investigate the relationship of factors that influence shale swelling. On the basis of previous studies, three factors – initial water content, clay fraction and confined pressure – were selected for analysis. In order to further understand the speed of shale swelling, investigations of specimens with different initial water/moisture contents swelling in water/humid conditions are summarized. The results show that water adsorption creates higher swelling volume than moisture adsorption and the maximum swelling speed occurs at an initial water content of about 14%. To measure swelling potential, a multiple linear regression model is developed to obtain an equation to predict shale's swelling potential. According to the regression results, shale swelling is negatively linearly related to initial water content and logarithmic confined pressure, and is correlated linearly with clay fraction.

Contents

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1. Introduction

The worldwide increase of natural gas consumption has promoted the recovery of unconventional natural gas, such as coalbed methane and shale gas. The estimated world resources of shale gas are about 22,016 Tcf, which is almost equivalent to the sum of other unconventional gas resources (coalbed methane plus tight sandstone gas) (EIA, 2011; Kuuskraa, 2006). Due to the development of drilling and recovery techniques, shale gas production has increased steadily in the past ten years. However, the large amount of fracturing fluids mixed with ground water which flows into shale through artificial and natural fractures influences wellbore instability and shale formation collapse (Al-Bazali et al., 2008; Chen et al., 2003; Chenevert, 1970; Makhanov et al., 2014). These effects are related to the movement of water and ions into or out of the shale (Zhang et al., 2004). Such movement may cause shale swelling, which alters shale's properties such as its permeability, strength, pore pressure and elastic modulus (Emadi et al., 2015, Emadi et al., 2013; Unrug, 1997).

Shale is a kind of fine-grained, clay-rich sedimentary rock which expands while adsorbing liquids or gas (White et al., 2005). The swelling of clay and shale has been investigated by numerous scholars. Skempton (1953) studied the relationship between plasticity index and clay content. The results showed that, for a certain clay, the ratio between plasticity index and clay content is constant, which named activity. O'Neill and Ghazzaly (1977) and Johnson and Snethen, (1978) built a model to evaluate the swelling percentage of clay which considered the liquid limit and the natural water content. Then the liquid index (LI), liquid limit (LL), plasticity index (PI) and plasticity limit (PL) were considered while modeling clay swelling potential (Abiddin Erguler and Ulusay, 2003; Chen, 2012; McKeen, 1992; Phanikumar and Muthukumar, 2015; Phanikumar et al., 2015; Snethen, 1984; Yilmaz, 2006).

As regards the shale swelling, Chenevert (1970) investigated the swelling alteration of montmorillonite shales, illitic shales and chloritic shales after adsorbing fresh water. The results showed that all the three types of shale presented a significant swelling percentage. Meanwhile, the swelling of many other types of shales are investigated, like La Biche shale (Wong, 1998, 2001), shale from the middle region of Saudi Arabia (Al-Mhaidib, 1998; Al-Mhaidib and Al-Shamrani, 2000; Al-Shamrani and Dhowian, 2003; Dafalla and Al-Shamrani, 2014), Bearpaw clayshale (Powell et al., 2013), Barnett shale (Heller and Zoback, 2014), Pierre shale (Teke et al., 2012), New Albany shale (Bryson et al., 2012) and so on (Ewy and Morton, 2009; Huang et al., 1986; Sherwood and Bailey, 1994). Ewy (2014), Hoover, et al. (2015) and Droghei and Salusti (2015) investigated the swelling characteristics of shales while adsorbing water, hydrogen peroxide and brine, respectively.

Several scholars have built prediction models for shale swelling. Brackley (1980) built a model to obtain the maximum movement of soil while swelling beneath a building. The model is written as follows:

$$S = \frac{PI - 10}{10} \lg\left(P_s / p_{of}\right) \tag{1}$$

where S is the swelling volume (%), P_s is the soil suction (kPa) and P_{of} is the overburden pressure plus foundation pressure (kPa), PI is the plasticity index.

Considering the effect of initial water content(W), liquid limit (LL) and clay fraction(C), Erol and Dhowian (1990) used the multiple and non-linear regression analyses to develop a model to predict free swelling potential of shale which is written:

$$S = 0.925(0.43LL - W)^{0.51} + 1.19PI^{0.40} + 0.74C^{0.25} - 4.14 \tag{2}$$

where LL is the liquid limit (%), W is the initial water content (%) and C is the clay fraction (<2 μm) (%).

Sabtan (2005) developed a multiple linear regression (MLR) model to estimate the expansion of 30 undisturbed shale samples. The linear empirical equation which incorporates plasticity index, initial water content and the clay fraction is written as follows:

$$S = 1.0 + 0.06(C + PI - W) \tag{3}$$

Gomez-Gutierrez et al. (2011) conducted slake durability and swell tests on unweathered shales, and the prediction equation is written:

$$S = 29.33 \exp\left(-0.064\sqrt{\frac{I_{d2}}{C}}\right) \tag{4}$$

where I_{d2}, which as a function of W, is the slake durability index.

When shale underground absorbs water, the confined pressure will influence its swelling potential. And the initial water content is closely related to the shale's water adsorption potential. However, in Eq. (1) the water content was ignored, and in Eqs. (2)–(4) the effects of in situ pressure was not concerned. Therefore, all the four models cannot estimate the shale swelling precisely. Meanwhile, quantification of the swell potential in terms of all influential factors is not feasible. In this study, the influences of clay fraction, initial water content and confined pressure on shale swelling are considered. First, we investigate the relationship of swelling to each factor separately. Then a MLR model is proposed to evaluate shale swelling.

2. Water interacts with clay minerals and cations by hydration and swelling occurs

Swelling occurs when the pore fluid chemistry changes (e.g., it is soaked in water) or the confining stress is below the swelling pressure. Swelling pressure means the average pressure in pores that leads samples start to swell. As shale cores absorb and/or adsorb moisture or water, the water molecules flow into the samples. Some elements, such as clay, are especially sensitive to water and expand to accommodate the extra mass. The swelling process can be divided into three stages, as shown in Fig. 1(Wong, 1998):

- Stage 1: water flows from outside into intramatrix pores by hydraulic flow.
- Stage 2: water moves from the intramatrix pores to the interlamellar pores by ionic gradient. Water interacts with clay minerals and cations by hydration and swelling occurs.
- Stage 3: fluid in interlamellar pores reaches equilibrium – the effective confining stress is sufficient to prevent both water osmotic movement and hydration.

3. Factors affecting shale swelling induced by water adsorption

3.1. Water content

Swelling occurs when a material obtains moisture or water. The initial moisture/water content in shale not only influences its swelling rate, but also affects the swelling potential.

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